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A SUMMARY OF UNDERWATER ACOUSTIC DATA

PART V
BACKGROUND NOISE

by

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PREFACE

This report is the fifth of a series which attempts to summarize existing knowledge about the parameters in the sonar equations. These relationships, which find application in many problems involving underwater sound, are stated in Part I of this series. As outlined in Part I, the objective of the Summary is to provide a condensation of some of the basic data in underwater sound for use by practical sonar scientists. The present report deals with the background noise which limits the detection of signals by underwater sound receiving systems. Both ambient noise and self-noise are included.

Earlier reports in this series, Parts I-IV, have been classified Confidential. On the recommendation of the Underwater Sound Advisory Group, the present report is classified Secret, as will be the remaining reports in the series.

The complete series of reports is listed below:

Part I - Introduction (July 1953)

Part II - Target Strength (December 1953)

Part III - Recognition Differential (December 1953)

Part IV - Reverberation (February 1954)

Part V - Background Noise (July 1954)

Part VI - Source Level

Part VII - Transmission Loss

Manuscript submitted May 26, 1954

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A SUMMARY OF UNDERWATER ACOUSTIC DATA PART V—BACKGROUND NOISE

INTRODUCTION

Background noise pertains to the unwanted sounds which interfere with and obscure a wanted signal. Of the various types of background, reverberation is usually excluded because of its peculiar origin and properties, and has been treated separately as Part IV of this Summary.

In dealing with background noise it is convenient and customary to distinguish between ambient noise and self-noise. Ambient noise is a property of the medium itself at the time and place of observation, irrespective of the hydrophone and platform which is used to observe it. It is "the composite noise from all sources present in a given environment; desired signals and noise inherent in the measuring equipment and platform are excluded"(1). Self-noise is that part of the background noise which is caused by the measuring system and the platform on which it is mounted. Self-noise is entirely man-made; noise sources such as the propeller of the ship on which a transducer is mounted, the streaming of water and entrapped air past the transducer face, and the vibration of the transducer mountings are all properly described as self-noise.

All background noise levels will be expressed in terms of the level of an equivalent isotropic noise field at the transducer. By "equivalent" is meant an equality in level, at the output of sonar set, between the response produced by this fictitious isotropic noise field and the background noise actually present. Noise levels will be given in terms of spectrum levels (i.e., energy in a one-cycle band of noise) and expressed in db relative to 1 dyne/cm^2. When a reference pressure of 0.0002 dyne/cm^2 was used in original reports, the reported values are here converted to 1 dyne/cm^2 by the subtraction of 74 db.

AMBIENT NOISE

In the dictionary (Webster's International Dictionary, Second Edition), the word ambient means "encompassing on all sides; surrounding, environing, as, ambient air." When a hydrophone is placed in the sea, it is truly encompassed by the noise field of the medium itself, and the level of this noise is called the ambient noise level of the sea.

There are many sources of ambient noise, the most important of which are listed in Table 1. Some of them have been given intensive study since the early days of World War II, and their characteristics are well known. Other causes of noise are local and transitory, while the importance of some in the wide spectral range now of interest in underwater sound is unknown. Table 1 shows some of the definitely known sources of ambient noise together with a brief statement of their general characteristics; further discussion of the sources of ambient noise will be given below.

TABLE 1
Sources and Characteristics of Ambient Noise

Source	Prevalence
Thermal noise, due to molecular thermal agitation of medium	at high frequencies (50 kc ±) in deep water. Forms the limiting hydrophone threshold above 50 kc ±.
Sea Surface noise, associated with waves	in deep water between 100 cps and 50 kc ±. It is the dominant source of ambient noise in this frequency range in areas remote from coasts. Varies with sea state.
Biological noise, due to snapping shrimp and various soniferous fish	locally, in shallow water, when certain types of organisms are present. Many soniferous forms of marine life are known. Most important are snapping shrimp in warm waters over rocky, coral, or shell bottoms, and croakers.
Man-made noise, including distant ships and industrial noise in noisy harbors	in and near harbors and shipping. Especially important at frequencies below 1 kc, where it is often the dominant source of noise.
Rain noise	in and near rainstorms. Probably negligible below 1 kc.
Shore noise, produced by breaking surf and waves on coasts	near coasts.
Turbulence noise, due to current flow over rocky bottoms	often the dominant source of noise in bottomed hydrophones and mine cases at low frequencies.
Hydrostatic pressures, produced by waves above the hydrophone	at very low (below 10 cps) frequencies in bottomed hydrophones.
Terrestrial noise, due to earthquakes, active volcanoes, microseisms, and distant storms	in deep water at low frequencies. Speculative; importance as a source of ambient noise not yet known.

AMBIENT NOISE IN DEEP WATER

By deep water is meant those locations far from coasts where the noise generated by shallow-water sources, such as harbor noise and many types of soniferous life, are absent, or at least known to be negligible contributors to the total ambient level.

Average Levels Above 1 Kc

Deep-water ambient noise was first studied during World War II, and the results of many wartime measurements have been summarized in the form of the well-known "Knudsen" curves showing the spectrum of deep-water noise and its dependence on sea state(2;3;4;5, p. 250). These curves are still accepted as being representative of average ambient levels in the frequency range 1-25 kc. However, recent work below 1 kc has shown deviations from the Knudsen values. Moreover, at frequencies above 50 kc, it is now realized that the thermal agitation of the medium imposes an upper frequency limit beyond which the curves cannot be extended.

Figure 1 reproduces the Knudsen curves in the frequency range 1-25 kc together with their extension (shown dashed) to the thermal spectrum limit. This limit, determined by the thermal excitation of the medium, sets an absolute upper limit to the sensitivity of measuring equipment. The thermal noise level in db relative to 1 dyne/cm^2 in a one-cycle band at a frequency f in kc has been shown(6) to be approximately

$$-115 + 20 \log f.$$

This function is plotted as the upward sloping straight line in Fig. 1. It applies for a nondirectional, perfectly efficient transducer. For a transducer with a directivity index D and an efficiency E (expressed in db), the corresponding expression would be

$$-115 + 20 \log f - D - E.$$

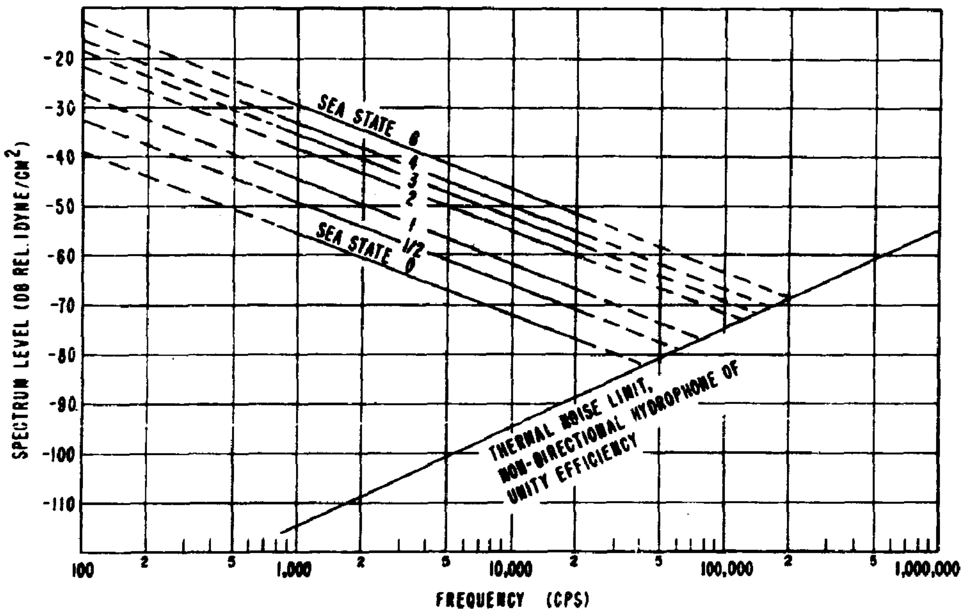

Figure 1 - Deep-water ambient-noise levels (Knudsen curves) for sea states 0 to 6

A characteristic feature of deep-water ambient noise is its variation with sea state, which must imply that deep-water noise originates in some manner at the ocean surface. The process by which noise is produced by the roughness of the sea has received little or no attention. At high sea states, it is likely that breaking wavelets and whitecaps contribute to the sea-surface noise. But, at low sea states, some other mechanism must be responsible for the increase in ambient level between sea state 0 and the sea state at which whitecaps first appear. One suggestion that may be advanced here is that ambient noise, at least at low sea states, has its origin in the atmosphere and is the result of wind turbulences produced by air motion across the rough sea surface.

Falling rain may be expected to increase ambient noise levels. One set of observations at 19.5 kc in steady, though not torrential, rain in sea state 2, showed ambient levels corresponding to sea state 6, an increase of about 10 db(7).

Average Levels Below 1 Kc

Postwar work on ambient noise has been largely concerned with the spectral region below 1 kc, and departures from the Knudsen curves have been reported below 500 cps. Measurements of ambient noise in this frequency region demand new techniques and new instrumentation in order to minimize the self-noise which arises from the hydrophone suspension and the influence of the measuring vessel. In one set of measurements, a bottomed hydrophone has been used in water depths as great as 50 fathoms(8); in other experiments a freely falling hydrophone, known as the "Diving Duck," without connecting cable and remote from the measurement ship, has been employed(9); and measurements with the deep-bottomed hydrophones of the Sofar and listening stations have provided much low-frequency data(9,10). Figure 2 gives a summary of recent deep-water ambient-noise measurements from surface vessels, with data by Woods Hole Oceanographic Institution from one station off Boston harbor in 22 fathoms included in the belief that it is not essentially different from deep-water data. Figure 3 presents typical ambient-noise spectra obtained with the deep shore-connected hydrophones at Pt. Sur, California, at Eleuthera, and at San Juan, Puerto Rico. The Knudsen curves down to 100 cps are shown also, for reference.

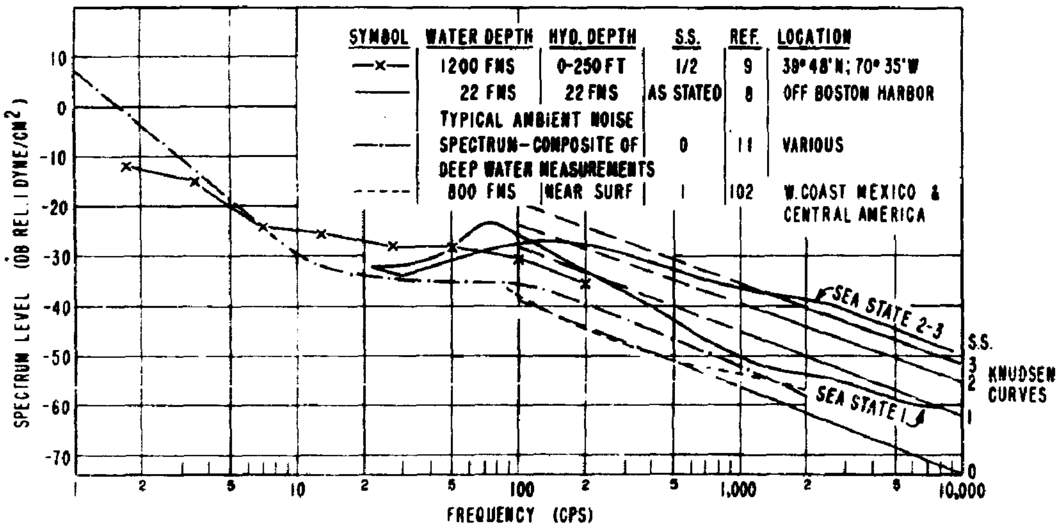

Figure 2 - Deep-water ambient-noise levels measured from surface vessels

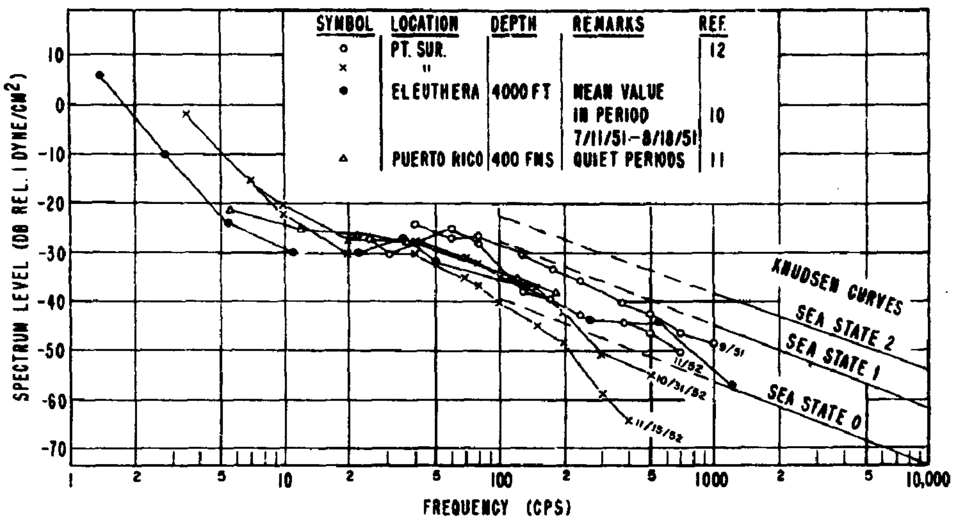

Figure 3 - Deep-water ambient-noise levels measured at bottomed hydrophones

Perhaps the most prominent feature of these low-frequency ambient noise spectra is the flat region in the decade 10-100 cps. The existence of this "plateau" is remarkably clear in the measurements of nearly all observers, in shallow water as well as deep, and its level appears to be well defined at between -20 and -30 db rel. 1 dyne/cm^2. The WHOI curves of Fig. 2 suggest that this plateau level is independent of sea state, although there are other data which do not confirm this(9). Below 10 cps, the spectra again slope upward with decreasing frequency at perhaps a greater rate (7 db per octave) than at several hundred cycles and above (5 db/octave). Measurements made by WHOI at stations mostly on the continental shelf south of New England show that the slope of the spectrum in the decade 100 to 1000 cps decreases with increasing sea state, being only about 3 db per octave for a wind velocity of 30 knots(13).

This peculiar shape of the low-frequency ambient-noise spectrum must mean that there are different dominant sources of deep-water noise in the different frequency regions. Indeed, it is probable that distant ships and other man-made noises are the principal sources of noise at low frequencies, even in deep water far from known ship traffic. Also, at ultralow frequencies, the hydrostatic effect of surface waves and swell must become important. We can do little else than speculate about these matters at the present time, and the identification of low-frequency ambient-noise sources together with the peculiar shape of the ambient-noise spectrum remain outstanding problems for future study.

Variability of Deep-Water Noise

One striking feature of the ambient levels at low frequency is their variability. It is common for measured levels to fluctuate from day to day or hour to hour without any apparent change in conditions. This variability is least at high frequencies and is greatest at low frequencies, especially near harbors and coasts where the highly variable man-made disturbances are important. The standard deviation of observed levels at high frequencies and in deep

water, where the Knudsen curves apply, is stated to be of the order of 4 to 5 db, and is less at high sea states than at low(2, p. 6). Much of this spread may represent uncertainty in the determination of sea state; indeed, ambient noise at frequencies greater than 1 kc may be an easy, and at the present time, the most accurate measure of sea state. It is possible, however, that wind force rather than sea state is the most representative correlative of ambient-noise levels, and the matter is closely connected with the process by which sea noise originates. At locations far from coasts, and when an equilibrium between the wind and the sea it creates has been established, wind speed and sea roughness vary together. In using the Knudsen curves, it is necessary to differentiate between sea and swell, since the long swells which create great wave heights probably do not contribute appreciably to ambient-noise levels at high frequencies.

Effect of Hydrophone Depth

If deep-water ambient noise originates at the surface, one might expect that its level would fall off with increasing depth as the distance from the surface sources becomes greater. This effect of hydrophone depth would be most noticeable at high frequencies where high absorption exists. However, no clear demonstration of a depth effect on ambient levels at high frequencies has been made. In the range 20-300 feet, observed ambient levels are stated to be independent of depth for frequencies at and below 25 kc(2, p. 2). A theoretical study shows that even at a frequency as high as 50 kc, the decrease in level between 3 feet and 300 feet should be but 3 db if each element of ocean surface radiates preferentially in a downward direction, as is reasonable(14). The depth dependence of ambient noise at 20 kc was the subject of a special British experiment, which showed no significant difference in level between the surface and a depth of 300 feet; this work was done, however, in shallow water at various locations in water depths between 15 and 50 fathoms(15).

When bottom-mounted hydrophones are employed, the low-frequency ambient noise due to the hydrostatic effect of ocean waves might be expected to become greater as the surface is approached. Figure 4 shows three ambient-noise spectra observed at the Eleuthera Lofar station with a bottomed hydrophone at depths of 40, 1000, and 4000 feet(10). Although the shallow hydrophone receives only slightly more noise at moderate frequencies, it is much more noisy below 10 cps, where the pressures produced by ocean waves become important. That this is a reasonable explanation is demonstrated by the triangular plotted point, which is the level for the 40-foot hydrophone computed on the basis of estimates of wave height and wave length at the time the ambient spectrum for this location was observed.

Although the depth effect on level is small, there is a definite difference in the character of ambient noise as observed on a very shallow hydrophone and on a deep hydrophone. Near the surface, ambient noise is characterized by large momentary increases of level—"spikes" on a recorder trace—that become less with increasing depth(7,15). These spikes may be the noise produced by individual breaking waves. As the hydrophone depth increases, the noise from the sea surface is integrated over a larger area, and a more uniform recorder trace results. However, for very shallow hydrophones it is difficult to distinguish between true ambient noise and the self-noise produced by breaking wavelets and water motion on and around the hydrophone and its support. A recently-reported change with depth of the spectrum of ambient noise, as observed with a wide-band hydrophone and a panoramic receiver(16) may merely represent a decreasing amount of self-noise as the hydrophone was lowered.

At hydrophone depths of a quarter wave length or less, the pressure-cancellation, or surface-image, effect of the surface gives rise to lower ambient levels. This near-surface reduction becomes important at low frequencies where the quarter-wave distance is within reach of hydrophones, although above 1 kilocycle it is negligible. In a recent series of measurements, a reduction of level amounting to 10 db between 90 feet and 10 feet was found at a frequency of 50 cycles(13).

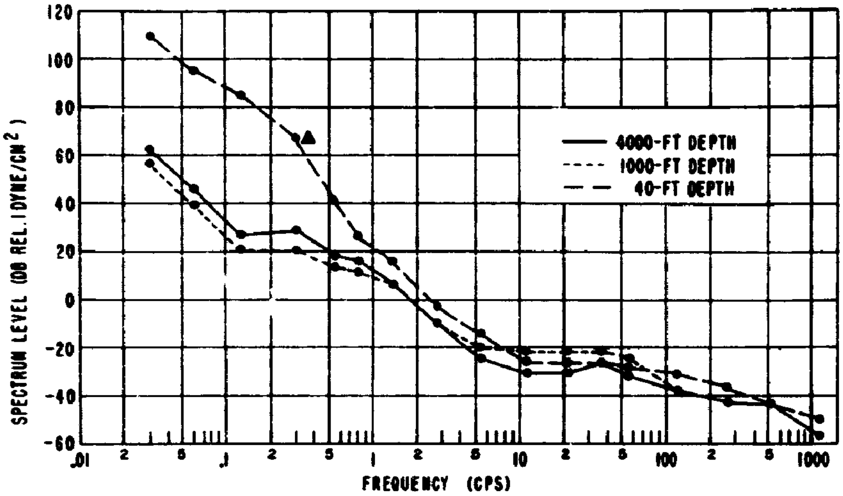

Figure 4 - Ambient-noise spectra at three bottomed hydrophones at Lofar Station No.2, Eleuthera. Average values are for period 7/11/51 to 8/18/51, sea states 1-2. (Ref. 10)

Effect of Sound Propagation Conditions

The possible influence of sound propagation conditions on ambient levels is a subject that has not received appreciable attention. It is possible, for example, that, for the same sea state, higher ambient levels would be measured by a shallow hydrophone in a good surface sound channel than in a poor one. There is one observation of a lower ambient level below the mixed layer than within it(17), and theoretical work using normal mode theory has been done on the effect of propagation on ambient noise in shallow water(18). However, the demonstration of a correlation between ambient levels and the transmission loss from a shallow source remains a problem for future investigation.

Directional Characteristics of Deep-Water Noise

Deep-water ambient noise is often stated to be isotropic. Yet, it cannot be so if it originates at the ocean surface and arrives at the hydrophone from upward directions. As a result, the directivity index for ambient noise will, in general, differ from the ordinary directivity index defined for isotropic noise. This was the subject of a theoretical study(14), which sometimes pointed to large differences depending upon hydrophone orientation and the presently unknown manner in which each element of surface radiates. In a field study the discrimination against ambient noise of a line hydrophone placed vertically and horizontally was investigated at 19.5 kc in deep water(7). No difference in apparent level between the two positions was observed. Although this would seem to indicate that ambient noise is isotropic, it has been shown that the same effect would be produced by many randomly phased surface radiators each radiating preferentially downward with a particular angular distribution of energy in a vertical plane(14).

AMBIENT NOISE IN COASTAL WATERS

In contrast to the relatively well-defined levels of deep-water ambient noise, the ambient levels in coastal waters, and in bays and harbors, are subject to wide variations. Because of the local and fluctuating characteristics of shallow-water noise sources, only very rough predictions of expectable ambient levels are possible.

For a given sea state, the deep-water levels described form a lower limit to shallow-water ambient levels. Because of the importance of noise sources other than sea surface roughness (Table 1), shallow-water levels are nearly always higher than the deep-water levels of Figs. 1 to 4 for the same sea state. The two most important additional sources of noise in coastal waters are the noise produced by soniferous marine life, and the man-made noise produced by ships and the industrial activity of harbors.

The noise produced by marine life was studied extensively during the war. Not only were the levels and character of the noise produced by various types of animals studied in the ocean and in laboratory tanks, but aerial surveys were undertaken to map the locations where such noise was important. This sort of work was continued at a lesser rate in the postwar years, until at the present time an extensive body of information exists on the sounds made by marine animals. The occurrence and some of the acoustic characteristics of soniferous life in the Pacific(19) and in the Atlantic(20) have recently been summarized. Many types of organisms are known to make sound and it is still not possible to associate all the sounds heard with particular noise-making animals. For instance, during a recent ambient noise survey(13), a strong peak in the spectrum at 1.5 kc, found over mud bottoms at stations south of New England, was suspected to be due to biological sources of some unknown type. Many sounds are so isolated in occurrence that they are of no importance as an interference to underwater listening. On the other hand, there are two types of animals—snapping shrimp and croakers—which are known to produce a chorus of sound that masks desired signals in extensive coastal areas. The average spectra of the sound from snapping shrimp, which are common in shallow hard-bottomed tropic locations, and representative spectra of the noise produced by croakers, which are common in Chesapeake Bay and other east coast bays, are given in Fig. 5. The interested reader must be referred to the literature(2,3,19,20) for information on the distribution of these and other soniferous species, and on the spectra of the sounds they create.

Man-made noise is typical of busy harbors and shipping lanes. Ship traffic is the dominant source of noise in many coastal locations, and even in deep water distant ships often create the principal part of the background at low frequencies. For example, from abundant data over the continental shelf and adjacent deep waters south of Cape Cod, it was concluded that ambient noise below 150 cps is due predominantly at these locations to distant ship traffic, although the noise above about 100 cps was believed to be associated with the ocean itself(18). In and near harbors, the miscellaneous noises of industrial activities are important. During the war years, ambient levels in bays and harbors of the east and west coasts, near certain Pacific islands, and in the waters near Great Britain were measured, and most of the measurements were summarized in a well-known report(2).

An outstanding characteristic of coastal ambient noise is its variability, not only from place to place in a single bay or harbor, but also with time at the same location. Both the biological and the man-made noise sources are often local in origin and subject to great changes in level. The variability in ambient levels is greatest at low frequencies and for low sea states. One example of the variability in coastal noise level is shown in Fig. 6, which gives two spectra obtained in an area 15-20 miles west of San Diego(21). Curve A is the average of weekday measurements when traffic and industrial activity in and near San Diego harbor was at its usual daytime level, while Curve B shows the average background level at the same place on weekends when the man-made noise was nearly absent. The ambient levels at remote areas

from 30-150 miles from San Diego were found similar to Curve B, which is close to the Knudsen curves for sea states between 1 and 2. The difference between A and B is greatest below 1 kc. Even larger differences between daytime and nighttime measurements were found during the war off New York harbor(2, p. 140). Daytime levels were 12 to 14 db higher between 200 and 2000 cps, although at 10 kc little difference between day and night was observed.

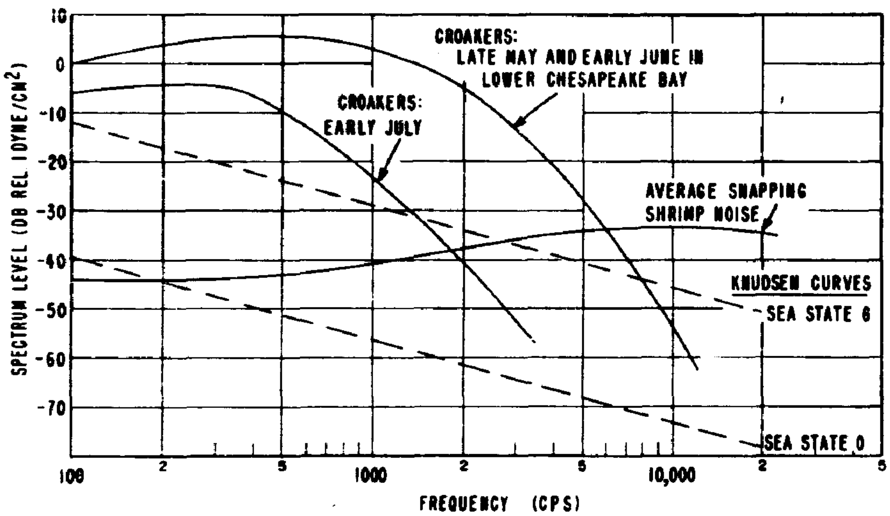

Figure 5 - Ambient-noise levels produced by croakers and snapping shrimp (Ref. 3)

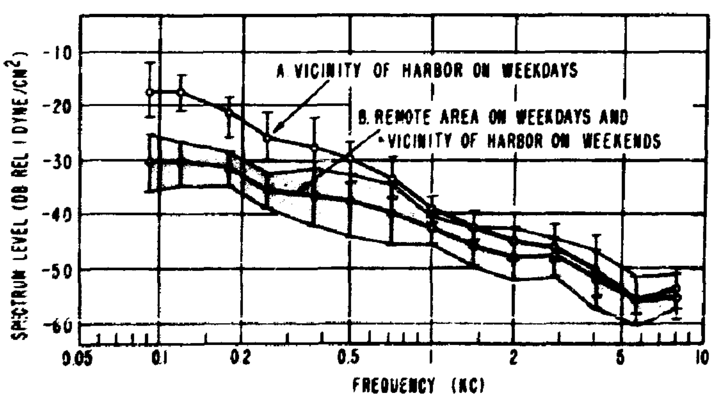

Figure 6 - Variation of ambient noise near San Diego. Vertical lines show limits of one standard deviation. (Ref. 21)

Because of this variability, it is difficult to give spectra of coastal ambient noise that may be regarded as typical. One attempt to give spectra representative of moderately and extremely noisy locations has been made(3). Figure 7, taken from this source, shows two spectra, one at the entrance to New York harbor in daytime, and the other in upper Long Island Sound near shipping lanes. The third curve is the deep-water Knudsen spectrum for sea state 2, which may be considered to be the lower limit for coastal locations. A working rule, established by the British by means of observations in shallow and deep water, is that the noise level in shallow water for a given sea state is 9 db higher than the corresponding figure for deep water(7). The variations in ambient noise for a given sea state from day to day and from place to place are greater in shallow than in deep water.

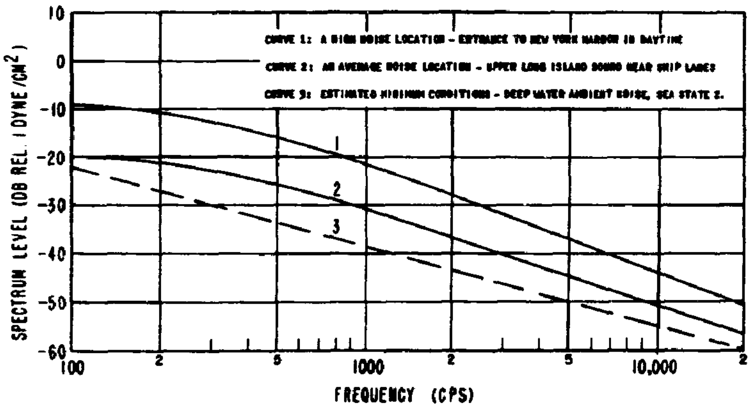

Figure 7 - Representative coastal ambient-noise spectra (Ref. 3)

For planning purposes, it is useful to have at hand composite spectra summarizing the available measurements, all obtained during the war. An average of the wartime measurements summarized in Ref. 2, extending along both coasts of the United States and to the Hawaiian Islands and Midway, in water depths from 3 to 30 fathoms, has been recently compiled(22). Figure 8, obtained from this source, shows average spectrum levels and their standard deviation for shrimp-free areas, and for areas where snapping shrimp are present.

Subsonic Shallow-Water Ambient Noise in Bottomed Hydrophones

The ambient levels to be expected at subsonic frequencies as measured by hydrophones in shallow water is of importance in the design of acoustic mines, some of which operate below 20 cps. This subject was studied during the war, and little or no postwar measurements are available.

This type of noise has several origins. Surface waves are known to create pressure effects at bottomed hydrophones that are indistinguishable from, and perhaps are properly called, sound (Table 1) in this frequency range. This type of noise increases with increasing water roughness. Another source of noise is caused by the flow of current which, in the vicinity of the hydrophone, creates turbulence at the rough bottom, transports bottom material, and causes eddying about the hydrophone structure. The action here is much the same as the low-frequency self-noise in submarine-mounted hydrophones when the submarine is under way. In bottom-mounted hydrophones, low-frequency noise is usually observed to increase when tidal currents become greater. Ship traffic also contributes to the background in this frequency range in the form of line components, especially at the blade frequency of the propellers.

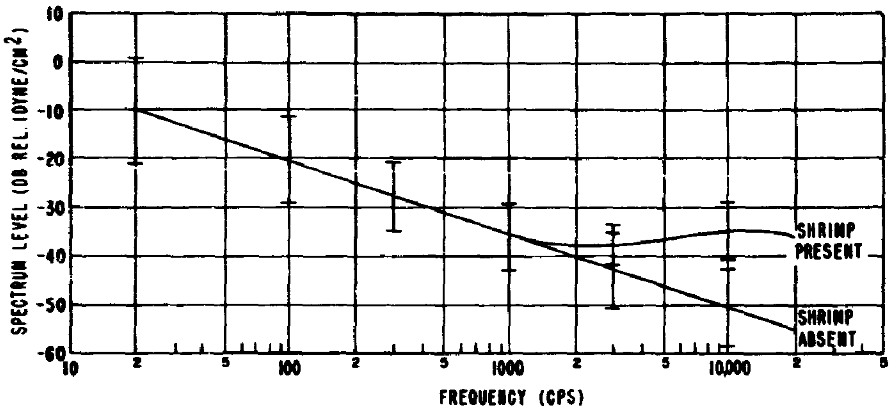

Figure 8 - Average ambient spectra in shallow water in presence and absence of snapping shrimp. Vertical lines show limits of one standard deviation. (Ref. 22)

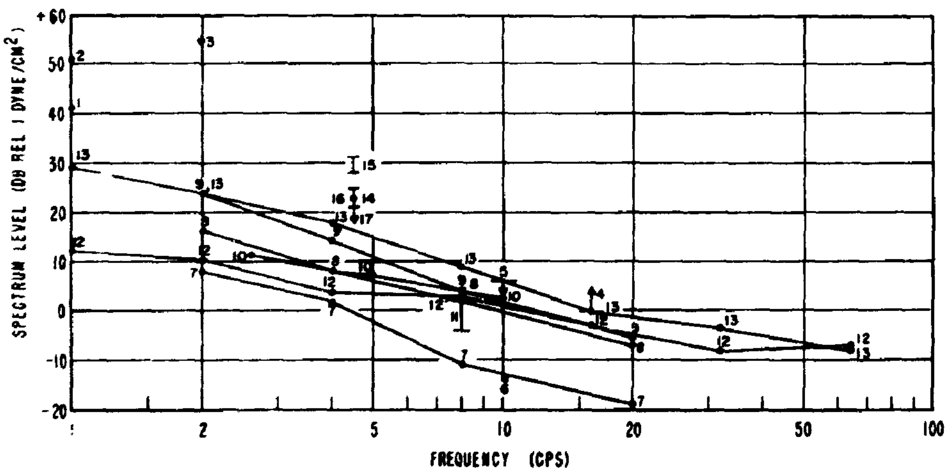

Figure 9 - Subsonic background in shallow-bottomed hydrophones, from plot of data listed in Table 2. Numbers refer to groups of data in Table 2.

Observations of this type of background are extremely discordant, and all that can be done is to indicate the order of magnitude of the pressures that have been observed in some instances. All of the data confirm a sea-state and tidal-current variation below 20 cps, and show a decreasing spectrum level with increasing frequency. Table 2 is a compilation of some representative reported values. Reduced spectrum levels are plotted in Fig. 9. In converting reported band pressures to spectrum levels, a spectrum of -6 db per octave was assumed, and the computed level was plotted in Fig. 9 at the geometric-mean frequency of the band.

TABLE 2
Reported Subsonic Background in Shallow-Bottomed Hydrophones

Serial No. in Fig. 9	Location	Water Depth	Reported Values: Band Pressure in dynes/cm²	Reported Values: Frequency Band, cps.	Converted Levels: Spectrum Level	Converted Levels: Midband Frequency	Reference	Conditions and Remarks
1	Near Woods Hole, Mass.	12' to 30'	150	1/2 to 2	+41	1	23	High surface currents, no waves.
2	Near Woods Hole, Mass.	12' to 30'	450	1/2 to 2	+51	2	23	High surface currents, waves present.
3	Near Woods Hole, Mass.	12' to 30'	1000	1 to 4	+55	2	24	At maximum current over a rocky bottom.
4	Near Woods Hole, Mass.	12' to 30'	>50	8 to 32	>0	16	24	At maximum current over a rocky bottom.
5	Nahant, Mass.	---	<20	1 to 100	<+6	10	23	A location open to the sea with a rocky bottom. On rough days, waves of more than 5 feet double amplitude were encountered. Reported value is instrument noise which was never exceeded by the background.
6	Inellan, Great Britain	110'	0.2*	6 to 16	-14	10	23	
7	Dunbar, Scotland	60'	3.5 2.6 0.8 0.5	2** 4 8 20	+8 +2 -11 -19	2 4 8 20	23	Calm days. Hydrophone 1200 yd offshore. Another hydrophone laid near rocks in 18 feet of water showed no difference in background amplitude or spectrum.
8	Dunbar, Scotland	60'	8 5 3.5 2	2 4 8 20	+16 +8 +2 -7	2 4 8 20	23	Moderately rough days.
9	Dunbar, Scotland	60'	20 9.5 4.5 2.5	2 4 8 20	+24 +14 +4 -5	2 4 8 20	23	Roughest days.
10	Halifax, Nova Scotia	90'	5 4.6 3.5	2 to 4 3½ - 7 7 to 14	+11 +7½ +2½	2.7 5 10	23	Moderately rough day.
11	Thames River, New London, Conn.	50'	5 to 10	1 to 64	4 to +2	8	23	Soft bottom.
12	Wolftrap, Chesapeake Bay, Va.	40'	3.8*** 3.1 1.5 1.6 0.7 0.4 0.45	1 2 4 8 16 32 64	+12 +10 +4 +4 -3 -8 -7	1 2 4 8 16 32 64	25	Minimum observed. May be largely self-noise resulting from cable vibration.
13	Wolftrap, Chesapeake Bay, Va	40	27 16 7.5 2.7 1.0 0.7 0.4	1 2 4 8 16 32 64	+29 +24 +18 +9 0 -3 -8	1 2 4 8 16 32 64	25	Maximum observed, maximum tidal current about 2-1/2 knots.
14	Stokes Bay, England	60' to 70'	30 to 50	2 to 10	+21 to +25	4.5	26	Estimated average value on a normal calm day.
15	Stokes Bay, England	60' to 70'	70 to 1[illegible]	2 to 10	+26 to +31	4.5	26	Estimated average value with a full gale and a choppy sea.
16	Barrons Point, England	90'	40	2 to 10	+23	4.5	26	Rough average value.
17	Southampton, England	48'	<30	2 to 10	<+21	4.5	26	Rough average value, protected water.

*Pressure in a [illegible] band lying in reported frequency band
**Octave centered at given frequency
***Spectrum level at given frequency

All of the measurements of Table 2 were made during the war, and in view of the uncertainties of calibration and analysis then existing, the reported values of some must be viewed with suspicion. Also, some measurements represent mostly instrumental noise rather than true ambient acoustic levels. Nevertheless, when taken as a whole, the compilation given may be useful for planning purposes. Much additional measurement work of both an analytic and a survey type is needed before other than extremely rough estimates of subsonic backgrounds become possible.

At frequencies below 1 cps, the background is probably entirely the hydrostatic pressures of ocean waves. One recent series of observations with a bottomed hydrophone in 90 feet of water at the entrance to Narragansett Bay, Rhode Island, indicated average peak to trough pressure variations at the bottom in a calm sea (sea state 0 or 1) corresponding to 3 inches of water,* with a 9-inch maximum(27). During a storm with a wind force of 7 and sea state 5, the bottom pressures rose to 15-inches average and 60-inches maximum. In both cases the average period of these variations was 10-11 seconds.

*1 inch of water at 4°C is equivalent to 2491 dynes/cm^2.

SELF-NOISE

While ambient noise may be described as being a characteristic of the natural environment of a receiving hydrophone, self-noise is essentially the result of its manner of mounting and of its means of travel on or through the sea. Self-noise is "the noise in the output of a specified sonar receiving equipment, inherent in the equipment and the ship or platform on which it is located, which interferes with the reception of the desired signal"(1). Because of the fact that self-noise is man-made, it is susceptible of reduction by various quieting schemes, and for the sonar engineer, the reduction of self-noise has been throughout the years an important problem capable of yielding large improvements in performance of underwater sound devices.

We will begin our summary of self-noise with a short discussion of the sources of noise and the paths by which noise reaches the hydrophone. A thorough knowledge of the sources of noise is essential for noise reduction and for understanding the many peculiarities of self-noise measurements made in the past. Since the major sources of noise are usually associated with the vehicle on which the receiving hydrophone is mounted, it will become apparent that self-noise is more a characteristic of the ship or platform carrying the receiving equipment than it is of the equipment itself. It is, therefore, convenient to treat self-noise primarily in relation to the platform or vehicle involved, such as surface ship, submarine, torpedo, etc.

In this report, self-noise levels will be expressed as isotropic or nondirectional levels referred to 1 dyne per square cm. The choice of expressing self-noise levels either as isotropic or as plane-wave levels is a difficult one. Neither way is entirely satisfactory over all frequency ranges and for all vehicles. Indeed, either reference is apt to lead to gross errors when the reported values are used in performance prediction for systems other than the one on which the original measurements were made, unless the user clearly and thoroughly understands: (1) the predominant noise sources for his system, (2) the acoustic paths by which the noise reaches the hydrophone, and (3) most important, the discrimination, or effective directivity index, of the system against the predominant source of noise. Although it is really immaterial whether a noise measured as a voltage at the transducer terminals is converted into an equivalent plane level or into an isotropic level, it is essential that the user of this information for a system other than the one for which the original data were obtained realize the type of noise he will be dealing with, and use the reduced data in connection with the directivity index that is appropriate to his particular system. In this summary we have preferred to use isotropic levels for two practical reasons. Since ambient noise is always referred to an equivalent isotropic noise field, the use of isotropic levels for self-noise as well yields uniformity in the sonar equations, because the terms N-D (where N is the isotropic level and D the directivity index) occur for both types of background noise. Also, the spread in reported values of self-noise appears to be much less when they are converted to isotropic levels than when they remain as plane-wave levels, making data obtained on the same class of ships with different transducers more directly comparable.* Indeed, it will be seen that self-noise levels measured with different systems are often brought into remarkable agreement in this way. However, it must be said in all fairness that the use of isotropic levels does have the great disadvantage of requiring for the conversion of a measurement an additional factor (the directivity index) which is not always known with any certainty either to the observer making the measurement or to the compiler of data; further, it may have no real validity in the particular circumstances of the measurement. Nevertheless, it appears that, of the two methods of expressing self-noise, the isotropic level is the more feasible for the present report. An exception will be made in the case of torpedo self-noise, where it is more appropriate to refer self-noise levels to the radiated or "external" noise level of the torpedo, and to use a special directivity index to express the discrimination of an internal hydrophone against this noise.

*This was found to be true during the war for surface ships at high frequencies(28).

A brief summary of the sources of self-noise and the paths along which the noise may travel from the source to the receiving transducer may be found in Table 3. Perhaps the most striking feature of this table is the wide variety of self-noise sources on naval vehicles, and the diversity of paths between the source and a mounted hydrophone. However, for any one vehicle only a very few of these will have any great contribution to the observed self-noise. Some brief comments about their relative importance are included in the table, and much additional discussion of sources will be included in the sections on particular vehicles to follow.

In spite of the importance of self-noise as a masking background in sonar, our knowledge of the quantitative importance of the various sources and paths is limited. Yet, it must be repeated that the subject is a vital one for self-noise reduction, for it is valueless either to expend effort on reducing the unimportant sources of noise, or to provide acoustic shielding for unimportant noise paths. Although a rather voluminous literature on self-noise exists, much of it describes isolated measurements on particular vehicles with individual transducers. Our limited knowledge of the sources of self-noise is largely due to the absence of any organized study of the subject until recent years. However, recently established programs, such as those at DTMB on submarine and surface ship self-noise, and the continuing program at UDE on surface ship noise, are making valuable contributions to our knowledge. Of all naval vehicles, the self-noise of torpedoes appears to be the best understood, possibly because it is comparatively easy to perform experiments.

One might expect that there should be considerable similarity between the sources of self-noise and the sources of radiated noise since all of them (with the exception of circuit noise) radiate some sound into the water. But their importance may be entirely different in the two cases. Certain sources of noise may be important for self-noise and unimportant for radiated noise because of their nearness, or because of the manner of mechanical coupling to the transducer; an example is the noise made by the striking of bubbles upon a dome around the transducer. On the other hand, some of the sources which largely determine radiated noise levels may be unimportant contributors to self-noise because of the shielding or acoustic isolation interposed in the primary path to the transducer; the rear baffle in surface-ship transducers reduces directly transmitted propeller noise in this manner.

One of the most important factors which determines the relative importance of the various sources of self-noise is the condition of the receiving equipment and of the noise and vibration sources associated with the platform. Defective and fouled domes on surface ships create hydrodynamic noise, and electrical noise may exceed other forms of self-noise in poorly maintained or electronically defective equipment. Equipment condition is largely a question of maintenance, and it will be assumed in what follows that the data refer to equipment in good operating condition unless the contrary is stated.

The self-noise of surface ships, submarines, torpedoes, and airborne sonar is a complicated and somewhat disorganized subject that has not yet had the systematic, intensive study it requires. Perhaps this is the result of the difficulties of conducting sustained shipboard studies and experiments pertaining to a branch of underwater sound that is characterized by a large number of independent variables. Its literature, with a few notable exceptions, consists of isolated occurrences and observations that are either not comparable or discordant. It will be evident that much of the following summary of this data will be more a compilation of reported effects rather than a complete treatment of a complex subject.

SELF-NOISE IN SURFACE SHIPS

Sources and Paths of Self-Noise in Surface Ships

Conventional echo-ranging sonar equipment aboard surface ships utilize directional transducers mounted in domes protruding from the bottom of the ship's hull. Domes were first employed in the period between World War I and World War II(29) for the purpose of reducing hydrodynamic noise. They are placed well forward in the vessel at a location determined perhaps more by space considerations than by any knowledge of optimum dome position for

TABLE 3
Sources and Paths of Self-Noise

Source	Paths	Character and Importance
MACHINERY NOISE AND VIBRATION (a) Main Propulsion (b) Main Shaft and Bearing (c) Auxiliaries	(i) Via hull to transducer support (ii) Via hull to water	Contains line components. Spectrum falls at about 12 db/octave above 1-2 kc. Important at low frequencies in submarines, surface ships, and ship-towed sonar.
PROPELLER NOISE	(i) Via direct path and reflection within dome (ii) Reflection and scattering from sea bottom (iii) Reflection and scattering from sea surface (iv) Reflection and scattering from other reflectors present in medium and introduced by passage of the vessel (v) Reflection, scattering, and reradiation from hull (vi) Shaft to hull	Continuous spectrum (cavitation noise) falling at 6 db/octave. Level increases rapidly with speed at inception of cavitation. Path (ii) particularly important for surface ships in shallow water. Path (iii) particularly important in torpedoes.
HYDRODYNAMIC NOISE (a) Flow Noise (i) Noise due to the eddies and vortices themselves (ii) Pressure variations on hydrophone element (b) Flow Excitation Vibration induced in transducer (or dome), hull superstructure, or cable support (c) Cavitation Around transducer (or dome), support, hull appendages, and imperfections (d) Bubbles (i) Striking dome (ii) Deformed in pressure field near dome (iii) Coalescing and breaking up near dome (e) Surface Waves Generated by ship's passage	Direct paths	Continuous spectrum (a,ii), (b) Important in submarine listening at low frequencies (c) Important on surface ships and torpedoes at high speeds. Importance in surface ships depends on condition of hull of dome (d) Important for surface ships. Importance depends on dome position and shape of hull (e) Of doubtful importance
CIRCUIT NOISE Thermal Noise Tube Noise Hum Microphonics	Generated within system	Contribution negligible in well-designed systems
MISCELLANEOUS (a) Helicopter Rotor Noise (b) Crew Movement	(a) Direct from air to water (b) As for machinery noise and vibration	(a) Limiting in helicopter-borne sonar (b) Important in submarine listening

quiet operation. Most self-noise measurements, and much of our understanding of the sources of self-noise, were obtained with, and refer to, such conventional installations of echo-ranging sonars operating at frequencies above 10 kc.

The pioneering attempt to separate the sources of self-noise was made by BTL during the war on the small ship ELCOBEL(30), a twin-engine motor launch 60-feet long. Although this vessel was far smaller than a typical combat or patrol craft, the results obtained at the time did indicate the general nature of the sources of self-noise. Subsequent work by many individuals in various laboratories has gradually improved our understanding of a complex subject. A program to study the sources of self-noise was established at DTMB about 1949.

To facilitate discussion, it is convenient to group the many sources of self-noise into three categories: propeller noise, machinery noise, and hydrodynamic noise. Propeller noise will denote the noise originating by cavitation at the propellers; machinery noise, the noise produced by the main propulsion plant and the auxiliary machinery of the ship; and hydrodynamic noise, the noise produced in various ways by the motion of the vessel through the water. These three principal sources have an importance relative to each other in their contribution to total noise level that depends upon many factors. We will give much attention to their relative significance because of the fundamental nature of this subject. The following discussion will be confined, unless stated otherwise, to the forward bearings of the directional transducer, since these are the directions of operational interest.

Propeller Noise - Possibly because propeller noise is the most intense and obvious source of noise at echo-ranging frequencies at the higher speeds of interest in surface ships, particular attention has been given to it in the literature as a source of self-noise. For example, in British trials (in 1941), conducted in a small motor antisubmarine boat using propellers of different sizes and pitch, it was found that propeller-tip speed rather than vessel speed determined the self-noise level; this clearly indicated that the propellers were the most important source(31). Similarly, it was found in wartime trials conducted by BTL in ELCOBEL that propeller noise was predominant at high frequencies(30). In fact, it appears that it was the generally accepted hypothesis for a long time that at high speeds propeller noise was the main source of self-noise(32). It is now realized, however, that although this is true in shallow water, propeller noise may be of negligible importance in deep water where the predominant noise is probably of hydrodynamic origin. The difference in the two cases lies in the influence of bottom reflection on the propeller noise contribution to the total self-noise.

For convenience we will first discuss the importance of propeller noise in deep water. There are a number of paths available for propeller noise to reach a transducer in deep water. These paths fall into four general categories: (1) direct paths including reflection within the dome; (2) paths along which the noise is deflected or scattered from reflectors or scatterers already present in the ocean, such as its surface, or is reflected or scattered from reflectors introduced by passage of the ship, such as the bow wave; (3) paths including reflection and reradiation from the hull; and (4) paths via the propeller shafts to the hull and transducer support. Information on the contributions of propeller noise arriving via these various paths is very limited. Yet, it is clear from a comparison of deep and shallow water self-noise levels, that these paths are much less important than the bottom reflection path in shallow water.

Of the four paths available in deep water, the direct path is probably the most significant. It was concluded, for example, as a result of British trials on HELMSDALE, in shallow water, using a pulser near the propellers, that in addition to the bottom reflection, the direct path was also important(33). If this is the case we would expect the contribution of propeller noise to vary markedly with the amount of shielding between the propellers and the receiver, and particularly with the absence or presence of a baffle. The latter was found to be important in DTMB studies of self-noise in QHB sonar in CVL's(34). In deep water it was found as a result of wake crossing trials that propeller noise predominated at 10 knots in SAIPAN (CVL 48) which had no baffle. In WRIGHT (CVL 49), which was fitted with a baffle, the importance of propeller noise was much reduced, and the propeller component of self-noise was about equal

to that of all other noise components at 20 knots. The major contribution to the noise in this vessel was probably of hydrodynamic origin. If the direct path is indeed the most significant one in deep water, as these results tend to suggest, we should expect that the importance of propeller noise in deep water would be greatest in small ships where the amount of hull shielding and the distance to the propellers is less than on large ships. Also, the domes are usually smaller on the smaller vessels, so that there is less opportunity for effective stern baffling. It is interesting to note, therefore, that it was concluded as a result of studies of self-noise in the EPC 618 conducted in water usually greater than 36 fathoms deep, that propeller noise was not a dominant source of self-noise(35) on forward bearings in QCU equipment, despite the fact that radiated noise measurements on this vessel showed that the propellers were extremely noisy for a vessel of its size(36). If the conclusion regarding the effect of ship size are of significance, we should not expect propeller noise to be important on operational bearings in large ships, where hull shielding and baffles are most effective.

The significance of reflection and reradiation from the hull was investigated in the EPC 618 trials using a noisemaker located near the propellers(35). It was concluded that this path was less important than the direct path. Regarding reflection and scattering from surfaces other than the bottom, such as the rough sea surface and the bow wake, it has been suggested that the contributions arriving by these paths are probably small compared with that of the direct path(37). On the other hand, it is suggested in the British report of trials in HELMSDALE, that the propeller modulation heard on operational bearings in this vessel in very deep water were transmitted by back-scattering from the bow wave or from the rough sea surface(33).

In summary, the limited data available on the importance of propeller noise suggest that it is probably less, and certainly no more important, than the noise of hydrodynamic origin on operational bearings in deep water (say, deeper than 30 fathoms). This conclusion, suggested during the war(28), is in agreement with British experience(38), and is supported by data obtained by DTMB on SARSFIELD (DD 837)(39). It was found on this vessel that the use of a streamlined tube assembly to reduce propeller noise resulted in no more than a 2-db lowering of self-noise levels in an AN/SQS-10 transducer in deep water. Further, it appears that the propeller noise reaching this transducer in deep water probably arrived by the direct path.

Before concluding any discussion of the importance of propeller noise, some reference should be made to the wake-crossing technique devised by the British as a means of estimating the proportion of total self-noise attributable to the propellers. In wake-crossing trials, the vessel being studied either turns and crosses its own wakes, or crosses the fresh wake of a second ship. During the time that its dome is within the wake, an increase of noise is observed as a result of the impact of the wake bubbles; later, when the wake lies between the dome and the propellers, a reduction in self-noise below its normal value is found because of the screening of the propellers by the wake bubbles. Much valuable information on the relative importance of propeller noise obtained by means of this British technique has been obtained. Unfortunately, most of the wake-crossing trials were made in shallow water, where the reflection of propeller noise from the bottom provided an additional complication in the interpretation of the results(34).

Hydrodynamic Noise and Domes - By hydrodynamic noise is meant the noise produced directly or indirectly by the motion of the ship through the water. It includes the noise produced by cavitation and turbulence about the hull, about the dome, and about other protuberances from the smooth hull, as well as the noise associated with bubbles striking the face of the dome. The noise produced by the wake and wave system generated by the ship is included, but it probably is of minor importance.

The importance of hydrodynamic noise was recognized long ago when spherical domes were adopted in this country, and when streamlined domes were used by the British before World War II(29). Old measurements with and without a spherical dome about a QC transducer showed a lowering of level by as much as 23 db at 25 knots, with a smaller reduction at 30

knots than at 25(30), probably because of cavitation on the spherical dome. Use of the spherical dome raised the speed, beyond which water noise became excessive, from 5 knots to 10 knots; the streamlined dome increased the speed of effective operation to 15 knots(29).

Domes help to reduce self-noise by minimizing turbulent flow, by delaying the onset of cavitation, and by transferring the source of hydrodynamic noise to a distance from the transducer(40). Possible sources of noise about domes include the turbulence of the stream, the turbulence and separation in the boundary layer of the flow around the dome, and the air bubbles entrapped in the flow near the surface of the dome(41). All modern domes are teardrop shaped, with a length-to-width ratio varying from 2 to 1 to 4 to 1, and are designed so as not to cavitate at any speed that can be reached by the vessel as long as the dome is in good condition. There is some evidence, however, that dome cavitation may occur if the vessel is rolling and pitching, as suggested by observations with the QHB sonar on the KEITH (DD 775)(42).

The role of air bubbles whipped into the sea near and at the bow of a moving ship, and carried by the flow against the face of the dome, was demonstrated by the British long before the war through the direct expedient of placing an observer inside a dome having a transparent window(30). A stream of bubbles was seen to arrive from the direction of the bow and to strike the dome, so as to produce a noise not unlike that of falling pebbles striking a plate. Bubbles have also been seen by subsequent observers. A periscope was installed on the WRIGHT (CVL 49) in a transparent blister on the hull forward of the sonar dome(34). Although no bubbles were observed at a speed of 15 knots, at 18 knots clouds of bubbles were seen, which obscured the view of the dome. Again, both the QCU dome at frame 18 and an after dome at frame 42 on EPC 618 were observed through viewing ports in the hull(32). The self-noise of the QCU transducer on forward bearings was believed to be unaffected by bubbles striking the dome as long as the sea state was less than 3-1/2. On the after dome, bubbles were thought to have increased the self-noise a fraction of the time at sea states 3 to 3-1/2. When this vessel was towed, cavitation bubbles were observed on the rudder, on the propeller hubs, and on various struts at the higher towing speeds, although it seems certain that the propellers would, when the vessel was self-propelled, produce much more noise than all these appendages near the stern(35). The effect of bubbles striking the dome was also determined by full-scale towing trials of a dome by DTMB in the towing basin(41). When bubbles about 0.3 to 0.8 cm in diameter were introduced into the flow, an increase in noise level of 21 db in the band 1-50 kc was observed at a speed of 17.5 knots; the noise intensity was found to be approximately a linear function of velocity, suggesting that bubble-caused noise is indeed of an impactive origin(41).

Protuberances and imperfections of the hull near and forward of the sonar dome, and of the dome installation itself, may produce hydrodynamic noise. An example is the high noise levels in some CVL's which were attributed to the flow in and around the space about one-inch wide between the retractable dome and the sea-chest(34).

British observations of self-noise in a bottom-facing flush-mounted echo-sounder hydrophone suggested that the flow of water over the face of the hydrophone was the principal noise source at speeds up to 16 knots(43), although at higher speeds bottom-reflected propeller noise seemed to be the dominant source of noise in shallow water for this hydrophone. However, the noise produced by turbulent flow (eddies, etc.), around tranducers in ordinary domes, is too small, in the absence of cavitation, to be significant for surface ships(37).

At the present time the origin of hydrodynamic self-noise is not completely determined. Sources such as the cavitation around the hull plating and on defective domes, the bubbles produced near the bow and carried against the dome by the flow, and the flow-induced vibration of the dome wall, are undoubtedly important. At high speeds, and at ultrasonic frequencies, hydrodynamic noise is often the dominant source of self-noise in deep water in the absence of a reflecting bottom for the noise sources located toward the stern.

<u>Machinery Noise</u> - By machinery noise is meant the noise and vibration produced by the main propulsion plant, the reduction gears and propeller shafts, the auxiliary machinery, and the underwater discharges of the ship.

Machinery noise has some characteristics by which it differs from the other sources of self-noise. Its spectrum is steeper than the spectrum of propeller or hydrodynamic noise, falling with frequency as rapidly as 12 db per octave above 1 or 2 kc(5,44). At lower frequencies its spectrum contains line components which give it a tonal quality different from the sound of propeller noise. Also (although conclusive evidence is not available) the level of machinery noise increases only slightly with ship speed. This lack of a strong dependence on speed, together with the steep spectral slope, are not the normal characteristics of self-noise on surface ships; they indicate that under normal operating conditions machinery noise is not an important component of self-noise. However, there are numerous observations of its dominance at low ship speeds and at the lower frequencies. For example, the enhanced importance of machinery noise at low speeds was demonstrated during NEL studies of the German GHG listening array in WITEK (EDD 848)(45). Greater slopes in the self-noise spectra between 200 cps and 10 kc were observed below 10 knots (11 db/octave) than above this speed (7 db/octave) as would be expected if machinery noise was more important at the lower speeds. This change in slope was accompanied by a change in the character of the noise from "the high-frequency hiss of hydrodynamic noise at the higher speeds to the low-frequency tonal sounds at the low speeds"(45). It is also reported that machinery noise was the predominant source of self-noise at 25 kc in QHB equipment aboard MALOY (EDE 791) at speeds up to 15 knots, at which speed water turbulence noise began to predominate(46). In similar equipment aboard WRIGHT (CVL 49) machinery noise appeared to be of major importance in shallow water at speeds up to 10 knots and possibly up to 15 knots, when propeller noise became predominant(34).

In agreement with these observations are the results of the extensive noise trials conducted by DTMB in EPC 618, showing that machinery noise did not appear to be important at speeds above 10 knots in the frequency range 1-30 kc. Unfortunately, the electrical noise during these tests was not low enough for the importance of machinery noise at lower speeds to be determined(32,35).

An analysis of background noise in QHB equipment aboard various destroyers has shown, however, that the noise associated with the main propulsion system may be important at quite high speeds at 25 kc(42). It was found on ZELLARS (DD 777) that raising the transducer inside the sea chest reduced the noise level at 12 and 18 knots by 8 db, but not at all at 25 knots. This suggests that hull-transmitted noise and vibration were important at the high speeds, perhaps due to propeller excitation of mechanical resonances of the hull. On 692 class ships, for example, hull vibration can even be felt as mechanical tremors at approximately 23 to 26 knots(42). It is of interest to note that three-bladed propellers appeared to be noisier than the four-bladed at these higher speeds. On KEITH (DD 775), it was found that background noise at speeds as high as 25 knots was affected by the method of firing of the engine-room boilers. Some correlation seemed to exist between noise level and the speed of the draft blowers, and there were indications that the noise of the boiler fires was contributing to the background(42). Other forms of machinery noise that have been reported are the noise of the condenser discharge(47,48) and of the reduction gears(49).

The relative importance of machinery noise, as compared with the other sources of noise, is greatest at low speeds. However, at zero speed, machinery noise at ultrasonic frequencies on quiet ships may be even lower than ambient noise as illustrated by the data given later in this report,* which commonly show levels close to the ambient level in deep water. Machinery noise may never be important on such ships because propeller and hydrodynamic noise begin to predominate as soon as the speed is increased. On noisy ships, however, machinery noise, together with wave slap against the hull, prevents ambient levels from being reached at zero speed and thus becomes the dominant source of self-noise at low ship speeds.

Importance of the Bottom Reflection - The importance of reflection and scattering of sound from the bottom in determining the relative importance of the self-noise sources cannot be

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*Figure 12

overestimated. Although the possible importance of this path was recognized during the war(28), sufficient attention does not appear to have been given to water depth as a variable in self-noise studies. The presence of the bottom in shallow water obviously affects self-noise levels by providing an additional path for propeller and machinery noise to reach the transducer. On the other hand, hydrodynamic noise remains unaffected by water depth. The importance of the bottom path in shallow water appears to have been first clearly demonstrated in the British frigate HELMSDALE, when it was shown that perhaps the most important contribution of propeller noise to self-noise on operational bearings arrived by the bottom path(33). In these trials, conducted in water depths up to 30 fathoms, a small projector was installed near the propellers; the use of short pulses permitted the separation of signals arriving via the bottom and via the direct paths. The bottom-reflected signal was almost invariably the greatest, even on stern bearings(33).

Some measure of the importance of the bottom path is provided(34) by the results of DTMB studies of self-noise in QHB Sonar aboard WRIGHT (CVL 49). Figure 10 shows that at 20 knots the self-noise levels on this vessel decreased by some 8 db on going from shallow water to deep water. Much greater increases, of about 25 db, were observed on stern bearings. Probably because of the installation of a baffle(34), the deep-water level was particularly low on this vessel. It was concluded that the principal source of self-noise changed with water depth. Hydrodynamic noise was probably the major source in deep water; in shallow water, machinery noise was probably most important at low speeds while propeller noise predominated at high speeds(34). Increased noise levels in echo-ranging equipment have also been observed by the British in shallow water. On a cruiser, self-noise levels in 13 fathoms of water were observed to be 4 to 5 db higher than in 30 fathoms, although no change of level was found between 30 and 1000 fathoms(38).

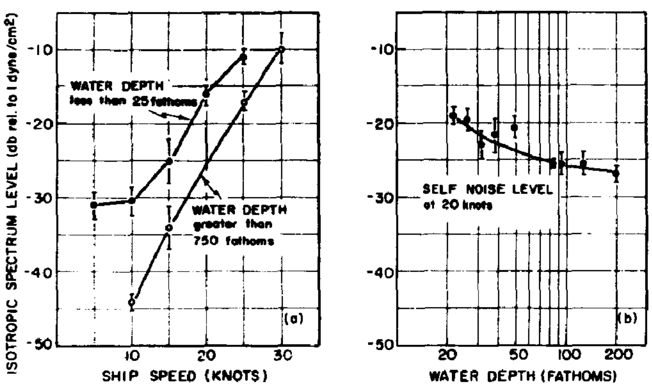


Figure 10 - Effect of water depth on self-noise in surface ships. Figure 10a shows the variation with speed for two water depths. Figure 10b shows the decrease in observed level in going from shallow to deep water. Data for OHB transducer in USS WRIGHT (CVL 49) on beam bearings (045, 090, 135, 225, 270, and 315), assumed directivity index 27 db, frequency 25 kc. (Ref. 34)

Relative Importance of the Sources of Noise - The various sources of self-noise on surface ships, which we have classified as propeller, hydrodynamic, or machinery noise, have an importance relative to one another which depends upon many factors, such as ship speed, water depth, frequency, and other factors. Some of these effects have been discussed above, and others will be given separate attention in the sections to follow. This subject of the dominant sources of noise under various conditions lies at the heart of the study of self-noise, and must be known before intelligent quieting countermeasures can be taken. It is a complex subject

responsible for the many scattered and often discordant observations and sound levels to be found in the literature. Much additional experimental and analytical work requiring considerable ingenuity is required before the sources of self-noise and their paths can be said to be quantitatively understood.

One way in which the relative importance of the three major sources of self-noise, together with ambient noise, can be indicated is on a diagram in which the two coordinates are water depth and ship speed. Such a diagram is shown in Fig. 11, where the areas in which the various sources are significant are shown by shadings of different sorts. On this diagram it is not possible at the present time to assign numbers to the scales of depth and range; indeed, the boundaries of the shaded areas are to a large extent a matter of personal judgment. Nevertheless, the broad features of the diagram are believed to be in agreement with our present knowledge of the subject.

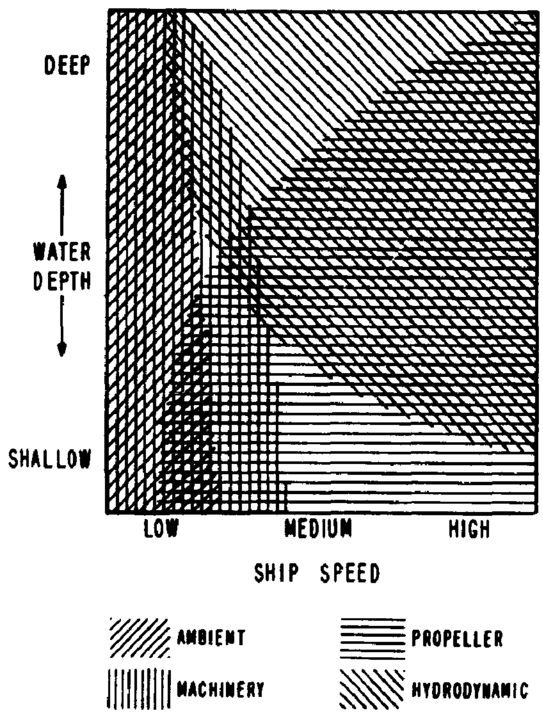


Figure 11 - Diagram showing the importance of the various sources of surface-ship self-noise at different water depths and speeds, over a hard bottom with a transducer in a dome at a frequency of 25 kc

One notes that over a large fraction of the area of Fig. 11, two or more sources are of nearly equal importance as contributors to the total self-noise. If we turn our attention to the four corners of the diagram, we find that in deep water at slow speed (upper left), ambient and machinery noise are the principal sources; as the speed is increased they are replaced by hydrodynamic noise (upper right). In shallow water and at low speeds (lower left), ambient and machinery sources are dominant, but they give way to propeller noise at high speeds (lower right). At intermediate depths and speeds (central area), several sources may be of nearly equal importance, and in individual cases, such as in a particular ship or over a particular

type of bottom, one source or another may dominate over the others. All these considerations illustrate the difficulty in expecting a single noise-quieting measure to be effective under all combinations of water depth and speed.

In conclusion, it must be emphasized that our knowledge of the relative importance of self-noise sources pertains largely to "conventional" systems under "standard" conditions—that is, to systems now, or at one time, in use in the fleet. One must accordingly feel some hesitancy in making extrapolations to the conditions and frequencies of future surface-ship sonars.

Self-Noise Levels

Effect of Speed - Of all the factors upon which the self-noise of surface ships depends, its variation with speed has received the most attention, probably owing to the ease with which the speed dependence of self-noise can be determined. Because of the fact that nearly all of the sources of self-noise become more intense as the vessel speed increases, self-noise levels always show a rise with ship speed. The rate of rise appears to depend upon the class of vessel.

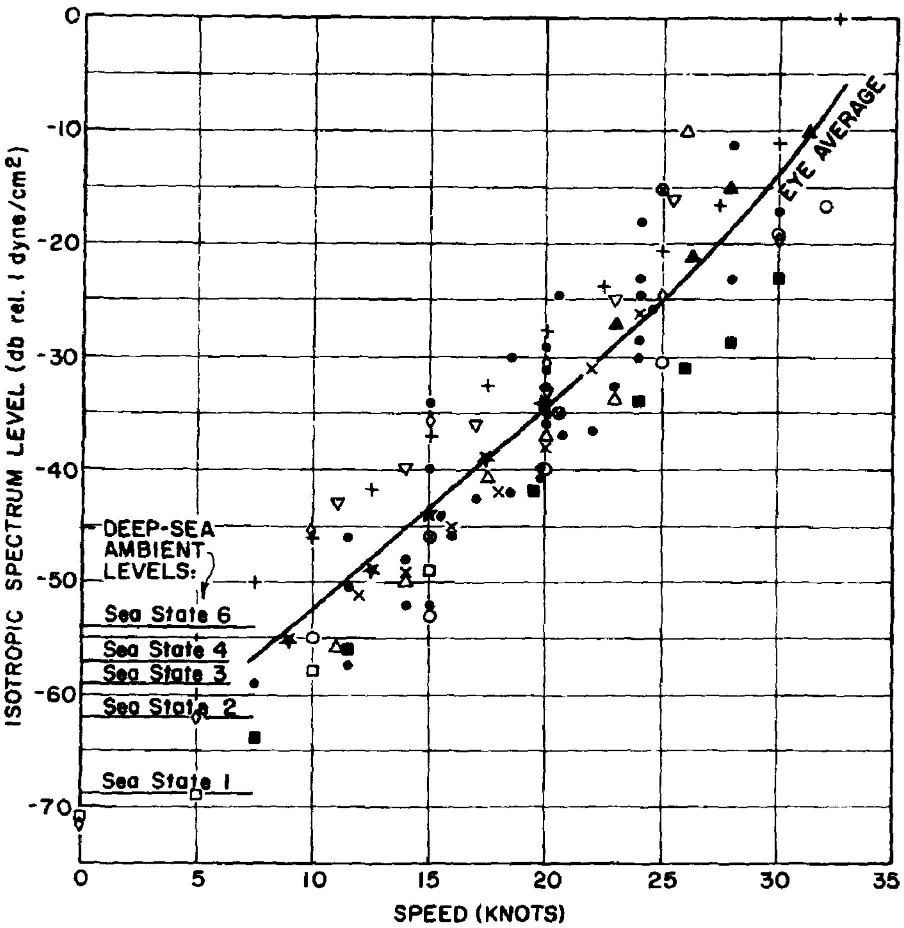
Figure 12 presents a compilation of many measured self-noise levels on destroyers. The plotted points have been taken from a variety of sources in the literature and were originally obtained with diverse sonar equipments and at different frequencies. Published levels, when given as equivalent plane-wave levels, have been converted to isotropic levels by adding a directivity index (estimated, for some equipments) and converted to 25 kc by applying a frequency correction amounting to 6 db per octave. Figure 13 is a similar plot for patrol craft.

It is amazing that in these plots the measurements are as nearly concordant as they are. Nearly all the points of Fig. 12 lie within about 7 db of the mean curve drawn-in by eye. The data were obtained with sonar hydrophones of widely different types, including searchlight transducers, scanning transducers, and even the GHG flush-mounted hull array on WITEK at frequencies in the range 10 to 30 kc. There is some evidence that Fig. 12 applies to any large vessel, regardless of type. A recent British conclusion is that there is little difference in deep-water isotropic self-noise levels between different ships and different domes when they are clean; the noise-speed curves for a cruiser (NEWFOUNDLAND), a destroyer (SAVAGE), and a frigate (HELMSDALE), all with different types of dome, were identical, within the limits of experimental error, in calm weather(38). Herein lies the principal benefit of the use of isotropic levels in expressing self-noise measurements. The plot for patrol craft (Fig. 13) contains fewer points having a greater scatter than the data of Fig. 12, possibly because of the great variety of hulls, of transducer location, and of auxiliary machinery on these vessels.

The indicated rate of rise with speed for destroyers is 1.8 db per octave up to a speed of about 23 knots, beyond which it is greater. This agrees closely with the well-known figure, used commonly in this country and by the British(38), of 2 db per knot, obtained largely from wartime data(30) (shown as solid dots in Fig. 12). A greater rate of rise with speed is indicated by the much sparser data for patrol craft, although some of the individual ships of this type do not show an appreciably higher rate of increase than do destroyers.

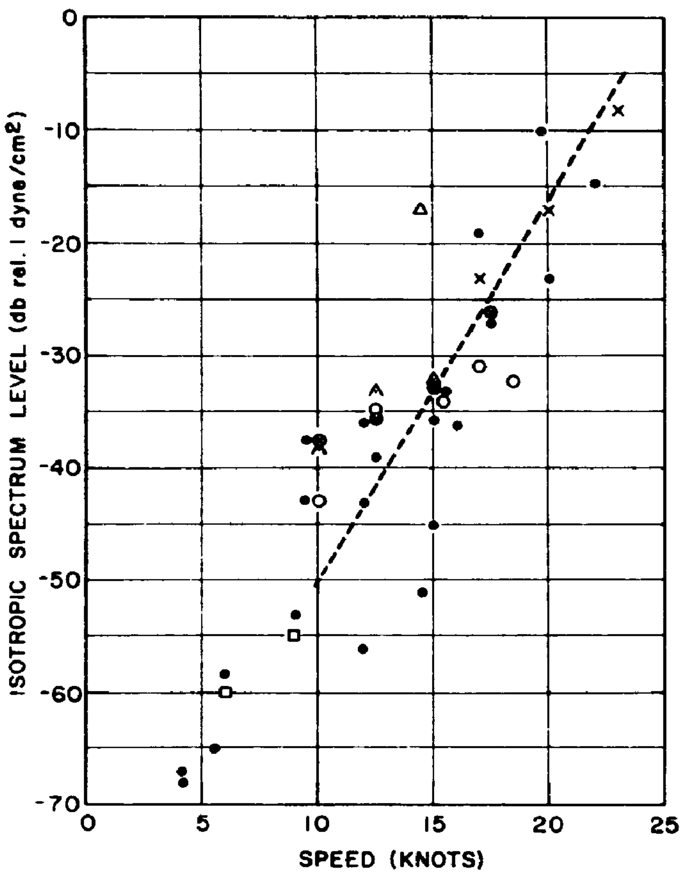
For vessels larger than destroyers, there have been only a few additional scattered measurements. One wartime measurement on USS COLORADO, a 19,000-ton tanker, indicated a 2-db-per-knot increase between 10 and 17 knots at 20 kc, with no increase with speed below 2500 cps(30), while a more recent measurement on a CVL, shown in Fig. 10, indicated about the same rate of rise as for destroyers(34).

At sonic frequencies (below 10 kc) one would expect to find a smaller rate of rise with speed because of the increasing importance of machinery noise. However, there have been no postwar measurements of the speed effect at frequencies below 10 kc other than with the GHG array on WITEK (EDD 848), which showed an increase of 1.2 db per knot above 10 knots in the range 250-10,000 cps(45). Wartime data in the range 1-10 kc showed an increase with speed of



- ● Wartime measurements, various ships and hydrophones, compiled in Ref. 30, Fig. 54.
- ○ XQHD in WITEK (EDD 848), NRL, quoted in Ref. 34 from Ref. 48.
- × QHB Sonar in clean domes, mean of 3 ships, USL, Ref. 42.
- □ QHB Sonar in MALOY (EDE 791), Ref. 46.
- △ QCA Sonar on DD 786, measured at 14 kc and corrected to 25 kc at 6 db/octave, Ref. 50. Best ship of 4.
- ▽ QCA Sonar on DD 783, measured at 30 kc and corrected to 25 kc at 6 db/octave, Ref. 50. Best ship of 4.
- + QHA in WITEK (EDD 848), D. I. assumed 23 db, Ref. 51.
- ■ HMS Savage, reduced to 25 kc, Ref. 52.
- ◊ GHG array in WITEK (EDD 848), measured at 10 kc & corrected to 24 kc at 6 db/octave. D. I. assumed 15.8 db. Ref. 45, Fig. 38.
- ▲ QCL-8 Sonar in WREN (DD 568). Average on port side after dome repair. Measured at 21 kc; band width assumed - 1.3 kc. Ref. 53, Figs. 7-10. D.I. assumed 21 db.
- ★ Mean for 3 British ships in deep water on operational bearings. Ref. 38 (corrected to 25 kc at 5 db/octave).
- ⊗ AN/SQS-10 Sonar in SARSFIELD (DD 837). Ref. 39.

Figure 12 - Self-noise levels at 25 kc in destroyers on forward bearings



● Wartime data on PC, SC, British DE's and Frigates, 24 kc, Ref. 30

× Mean of 3 DE's (DE 644, DE 641, DE 304), measured with QCT sonar at 20 & 21 kc and corrected to 24 kc, D. I. assumed 21 db, Ref. 50

△ Mean of 2 PCE-R's (PCE-R 855 & 857) measured with QCQ-2 sonar at 22.5 kc and corrected to 24 kc, D. I. assumed 22 db, Ref. 50

○ EPC 618 with QCU sonar at 25 kc, D. I. assumed 24 db, Ref. 32

⊕ EPC 618 with QCU sonar at 25 kc, more recent data, Ref. 34, Fig. 11

□ EPCE-R 851 at 15 kc, corrected to 24 kc, D. I. 20 db, Ref. 49

^ PCS-1426, 25 kc. Fig. 11 in Ref. 54

Figure 13 - Self-noise levels at 24 and 25 kc in patrol craft on forward bearings

from 1 to 3 db per knot for destroyers at speeds between 15 to 24 knots(30). On two smaller vessels (ELCOBEL and USCGC MADALAN) an increase of 5 db per knot was found between 500 and 10,000 cps(30).

At speeds below 10 knots, most measurements show a smaller rate of rise with speed than at the higher speeds. This is due to the fact that on most ships, a speed-independent noise

source, such as ambient noise or auxiliary machinery, is dominant at slow speeds. Figures 12 and 13 show the deep-water ambient levels at 24 kc for different sea states, which form the lower limit, on the average, for all self-noise measurements.

Spectrum of Surface Ship Self-Noise - Postwar work on self-noise has provided little additional information on its frequency dependence. From wartime data it was found that the self-noise of destroyers, after correction to isotropic levels, had a slope of from -5 to -7 db per octave (average, -6) at a speed of 20 knots between 10 and 30 kc(30). At lower frequencies (1-10 kc) the spectral slope was also -6 db per octave, on the average, in the speed range 10 to 24 knots, with no data below 10 knots to justify analysis(30). Also, the slope for patrol craft was found to be about the same for destroyers, with the somewhat uncertain exemption of the ELCOBEL, which had a slope of perhaps -4 db in the range 10-40 kc.

The prevalence and general validity of the -6 db per octave spectral slope is indicated by the agreement of measurements made at various frequencies, as shown in Fig. 12.

The wide prevalence of this value of -6 db/octave for so many types of craft and conditions is all the more remarkable when one considers the diverse origin of self-noise commonly encountered in ranges of speed, water depth, and frequency. Machinery noise, at least below 10 kc, certainly has a steeper slope. Indeed, a steep spectral slope is often taken as an indication of the strong presence of machinery noise, as with the GHG installation on the WITEK, which at slow speeds and for frequencies below 5 kc, had a spectrum with a slope of -11 db per octave(45). There is apparently some evidence to support the belief that hydrodynamic noise also has a steeper slope(38), such as the old observation that with the electrically steered array on ELCOBEL the slope of this "flow noise" is about -12 db per octave(30), with indications of a higher slope for destroyers (-8 db/octave) travelling at high speeds of 24 knots and above(30). Although it is clear from radiated noise measurements (in which at high frequencies the propellers are essentially the sole source of noise) that propeller noise has a continuous spectrum with a slope of -6 db per octave,* there are no really definite results on the spectral shape of other sources of self-noise. This remains an important problem that has not received analytical study since the war, but one which is essential for understanding and identifying the sources of self-noise under different conditions.

Directional Characteristics - The directional properties of self-noise in the horizontal plane are illustrated by polar patterns obtained by rotation of a directional transducer within a dome. These patterns commonly show a more or less uniform level on forward bearings within an arc of 120° either side of the bow, and have a broad increase at 180° in the direction of the propellers and the propulsion machinery. The prominence of the stern lobe of the polar pattern depends upon the relative importance of propeller noise and the presence or absence of a baffle in the dome. In the smaller ships such as SC's, PC's, and DE's, where the distance to the propellers, the amount of hull-shielding against propeller noise, and the size of the dome baffle are all less than on larger vessels, the stern lobe is often 25 db higher than the level on other bearings(30). On an SC (AMANDA), measured during the war, the self-noise level at 180° with QCU sonar at speeds between 8 and 18 knots was 23 db higher than that on the forward bearings(30). On a destroyer (NOA) a somewhat smaller lobe was observed, varying from 10 to 20 db at 24 kc with a QC hydrophone between 12 and 30 knots; on a second destroyer, SEMMES, it was from 4 to 9 db higher than the level at other bearings(30). The stern lobe is also somewhat less at sonic frequencies than at ultrasonic frequencies(30). All these are wartime observations. However, the size of the stern lobe depends upon the amount of shielding against noise from the stern that is provided by the dome baffle. Although on the EPC 618 with QCU sonar, the stern peak exceeded the forward-bearing levels by about 10 db at 10 knots and 25 db at 17.5 knots (Fig. 14a), no increase at all at stern bearings was commonly observed with the QHB sonar installed on various destroyers (Fig. 14b).

*It is remarkable that its spectrum is so nearly like that of ambient noise.

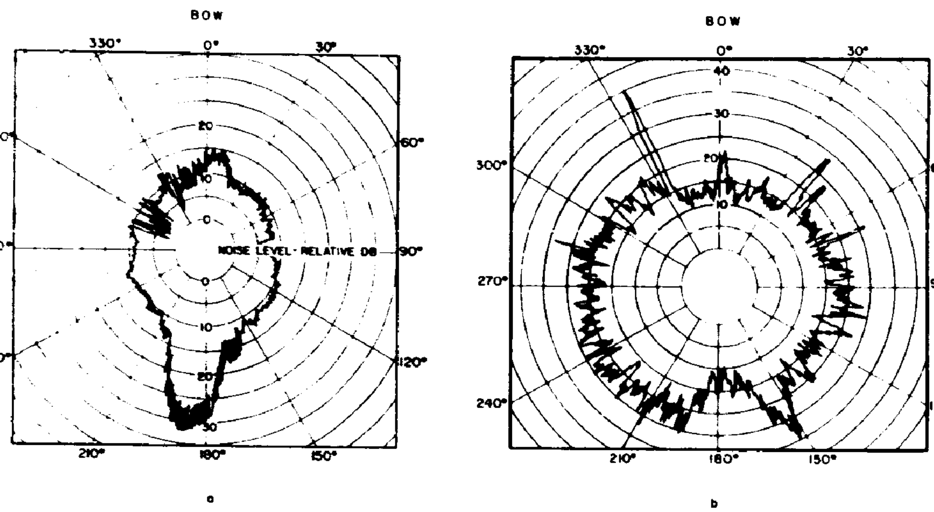


Figure 14 - Two sample polar diagrams showing the directional characteristics of surface-ship self-noise with db values relative to an arbitrary reference. Figure 14a is for the QCU searchlight sonar at 25 kc on EPC 618 at 12 knots. Figure 14b shows QHB self-noise for different directions of the listening beam on USS KEITH (DD 775) at 14 knots and includes time variations amounting to 15 db in 60 seconds due to bursts of energy of short duration. (Ref. 35 and 42)

Reported self-noise levels such as those compiled in Figs. 12 and 13 refer to the mean level on operational bearings, that is, within the forward semicircle. The usual uniform levels in this sector probably account for the success of the ordinary directivity index for comparing measurements made with different transducers. However, the polar plots of self-noise are not always as simple as this. With the XQHD scanning sonar on WITEK (EDD 848), for example, a high level that appeared to arise from an underwater condenser discharge was observed at one bearing at low speeds(47,48). A similar discharge, reported by the British, produced at 20 kc a level at slow speeds equivalent to the normal noise astern at a speed of 15 knots(55). Sometimes, domes and other hull protuberances forward of the hydrophone location create cavitation that gives rise to a peak at bearing 000, such as was observed at higher speeds during the XQHD measurements on WITEK (EDD 848), where a dome and a sonar sword forward of the XQHD dome created higher levels on the forward bearings(47,48).

A polar pattern, the reverse of the normal one, showing higher levels on the bow and the lowest levels on the stern, was observed by DTMB at 25 kc on WRIGHT (CVL 49) in deep water(34). The higher levels at 000, which averaged 5 db higher than these at off-bow bearings at speeds between 10 and 30 knots, were believed to be due to bubble streams impinging upon the dome(34). Evidence for the presence of these bubbles was provided by observations with an underwater periscope.

<u>Fluctuation of Self-Noise—Effect of Sea State</u> - As with all other types of noise, self-noise is not constant with time, but shows long-period and short-period variations. These fluctuations of level have various causes.

In one instance, long-period, day-to-day variations in level amounting to as much as 20 db were attributed to improper functioning of the training servo(35). But in most instances the day-to-day variation of the mean self-noise level is not large. For example, the day-to-day variation in the level of the QHB sonar on MALOY (EDE 791) was but 4 db or less at a speed of 12 knots(46). Sea-state changes may also give rise to day-to-day variations, as shown by

measurements at 25.6 kc between 10 and 17 knots of EPC 618 under tow, which indicated an increase of average self-noise level between sea states 0 and 2, together with a slight decrease between sea state 2 and 2+ (35). Also, the scatter of the measurements was greater for sea states greater than 1 than for sea states less than 1. That the average effect of sea state is slight was indicated in QHB measurements in various destroyers, which, in the higher sea states, gave lower levels at some ship's courses with respect to the sea than at other ship's courses in lower sea states(42). This small mean effect of sea state on self-noise, at least for low sea states, was shown also by wartime data and opinion(50).

On the other hand, sea state does produce large short-time fluctuations in self-noise level through its effect upon the roll and pitch of the vessel. In these QHB trials, noise bursts with a maximum intensity of 15 db above the normal self-noise level at 12 knots were observed to occur simultaneously with the rise and fall of the ship(42). These were not believed to be wave slaps, but rather the effect of cavitation on the dome caused by nonforward motion through the water. Short-time variations, produced by pitch and roll in the British frigate HELMSDALE, amounted to 20 db at 8 knots, but only 10 db at 18 knots, possibly because of less pitch and roll of the vessel at the higher speed(38). On WREN (DD 568), a change of level of 7 db was observed in sea state 3 at 20 kc in deep water when the ship rolled, and an even greater change was found when the ship pitched(53). It should be noted that in this vessel the effect of ship motion was accentuated by the forward position of the dome (at frame 25) compared to its normal position in other classes of destroyers (near frame 60). However, the effect of wave slap against the vessel in producing bursts of self-noise must not be discounted, as there are many recorded instances of its occurrence, such as old observations by BTL(30), and the observation by DTMB on the USS WRIGHT (CVL 49) of occasional peaks in self-noise which coincided with the sound heard in the lower sound room of waves breaking against the ship(34).

Other short-time fluctuations, or "crashes" of self-noise received intensive study with the GHG array on WITEK (EDD 848). These crashes had a peak level 5 db higher than the average level at 2 to 3 kc, and 20 db higher at 10 kc, with a maximum amplitude at a speed of 12 to 13 knots, when their peak level was higher than the average level at 27 knots(45). Although they were of short duration and occurred only every 10-30 seconds, they made listening impossible 50% of the time. The origin of these crashes was undetermined, although it is likely that they were associated with bubbles striking the face of the array.

In discussing the variation of self-noise, one must not overlook the large changes in self-noise over long periods of time which accompany deterioration of the dome(42) or of the electronic system.

Effect of Maneuvering - A subject not too often discussed in the literature is the effect on sonar self-noise of maneuvering or turning of the vessel. Little comparative data on self-noise with the ship on a straight course and in a turn appear to exist. Some such effect may be surmised because of the increased cavitation at the rudder and near the propellers in a turn. Another factor is the deflection of the bow wake and of the stream of underwater bubbles striking the dome. During the EPC 618 trials carried on by DTMB, variations of noise with rudder angle were observed on two flush-mounted hydrophones located at the stern on either side of the screws(35). The noise level was found to increase or decrease depending on the direction of turn and the side of the ship on which the hydrophone was located. This rudder effect was believed to explain some peculiar results found while this vessel was being towed (where, in order to avoid the wake of the towing ship, an almost continuous rudder angle was employed), such as the observations of higher self-noise levels while being towed than when self-propelled. Trials aboard EPC 618 using the standard sonar (QCU) showed an increase in level of 25 db at a bearing of 180° when rudder was applied although no change was observed at 0° or 90°, in agreement with the conclusion that noise coming from the stern was not important on the forward bearings(35). Another observation of an effect of a turn on self-noise levels was made during the GHG tests on WITEK (EDD 848), when the noise level in a turn was as much as 15 db higher on the inboard array than on the outboard array, and varied with both speed and rudder angle(45).

Effect of Dome Location - There have been only a few observations pertaining to the subject of the optimum location (for minimum self-noise) of the dome on a surface vessel. During the war, there was one observation of a lower self-noise on a merchant vessel when the draft of the ship increased from 20 feet to 24 feet 6 inches; the decrease was 15 db at frequencies above 5 kc, with little or no change at frequencies below 2 kc(30). Although this effect was believed to be due to the breaking of water by the propellers at the shallow draft, many other causes may be surmised. Some evidence of lower levels on vessels of deeper draft was also obtained during the QHB tests on destroyers(42). With the GHG array on WITEK, the crashes of noise that were so troublesome on this array were greatest in amplitude and frequency of occurrence on the shallower hydrophones(45).

During the tests of the GHG equipment, several monitor hydrophones at various locations on the hull were used. Those hydrophones aft of frame 60, where the XQHD sonar was located, were noisier than those forward of this location(45). This was attributed to a larger proportion of machinery noise received on the after hydrophones, as evidenced by the slower rate of rise of self-noise with speed in these hydrophones. Some of the monitor hydrophones were located on the keel of the WITEK, others part way up the hull. Those on the keel were about 6 db quieter than the off-keel hydrophones located nearby. Of all the keel-mounted hydrophones, those located between frames 20 and 40 were the most quiet at a speed of 25 knots.

The extensive trials conducted by DTMB on EPC 618 also provided some evidence of the effect of dome location on self-noise. Self-noise data were recorded with a hydrophone in a dome at frame 42 as well as with the standard QCU sonar in its dome at frame 18. The results of comparison measurements when the vessel was towed and when it was self-propelled showed that although propeller noise formed the principal component of self-noise at the after location, no propeller noise could be observed at the forward hydrophone on forward bearings(35).

Effect of Equipment Condition - It is well known that of all the factors which affect self-noise, the condition of the dome, the transducer, the training mechanism, and the electronic gear is perhaps the most important single determinant of self-noise in surface-ship sonar. We have been assuming in the discussion so far that the sonar equipment is reasonably well designed and maintained, and is free from obvious electronic and acoustic defects. Yet, it is obvious that this will not always (indeed, perhaps not even ordinarily) be the case for equipment in operational use, and some discussion of the effects of improper design and maintenance is necessary.

During the war, it was a common observation that the self-noise at slow speeds was principally the electronic noise of the receiver amplifier(50). On some ships, the speed had to be increased to about 17 knots before measured levels increased by 3 db. This condition caused a wide spread (amounting to 30 db at 14 kc) between measured levels at slow speeds in ships of the same type. Even more recently, on the experimental vessel EPC 618 which was studied exhaustively by DTMB, circuit noise caused difficulties and the electronic noise and vibration of the QCU training mechanism were found to create more noise than the noise associated with the ship(35). Also, in the QCL installation on WREN (DD 568), the motor-generator set supplying polarizing current to the transducer was found to be a source of electrical noise at 20 kc(53). Occurrences such as these are often vexatious and troublesome, but their diagnosis on shipboard is not too difficult, and their cure is usually apparent.

A less obvious source of abnormal self-noise, but one which has received much recent attention, is the condition of the sonar dome. That a faulty dome can cause a large increase in self-noise was made strikingly evident by the wide differences shown between measurements with the QHB sonar installed on 22 destroyers(42). A spread of 36 db between the noisiest and the most quiet ship was found at a speed of 12 knots; this spread decreased to 27 db at 25 knots. These noisy domes were fouled by barnacles and corrosion. When the domes of two relatively quiet ships were cleaned during yard overhaul, the self-noise levels dropped between 3 and 18 db below their preoverhaul values, and it was believed from all the data that keeping

the dome smooth and in repair would lower the background of some ships by as much as 30 db(42). Barnacle encrustation not only causes cavitation at the dome face at relatively low speeds, but reduces the level of the echo by causing a certain amount of attenuation as well. The British have also found that barnacle growth gives greatly increased noise(55). In one series of experiments, the effect of barnacles was simulated by attaching copper bands punched with jagged holes to the outside of the dome. More recently it was found that the smoothness of the outer surface of the dome greatly affects noise of nonpropeller origin(38). Reductions of 10 to 20 db at a speed of 18 knots may be achieved by removing a thin calcinous deposit (which a coat of antifouling paint would help prevent) and by subsequent polishing of the dome surface. Marine fouling by barnacles also occurred on the GHG array on WITEK, producing an increase in self-noise of 10 db in one month after cleaning during dry-docking; the difference in level between the most-fouled and the clean condition amounted to 20 db(45).

Domes may have other defects as well. On one of the destroyers on which the QHB self-noise measurements were made, a great accumulation of mud inside the dome was discovered upon dry-docking(42). On WREN (DD 568), the dome was found to have tiny holes where the welds had torn loose; on plugging up these holes, the high noise level which was previously observed dropped by 10 to 20 db(53). These examples all illustrate the necessity of keeping the dome in good condition in order that self-noise level be no higher than that in a reasonably quiet ship.

SELF-NOISE IN SUBMARINES

Sources of Self-Noise in Submarines

Submarine transducers are primarily used for listening rather than for echo-ranging. The frequencies of interest are in consequence lower than those in surface ships, and cover a wider range. The self-noise in JT transducers, for instance, has been measured from about 50 cps to about 10 kc, while wartime measurements on the JK listening transducer were made as high as 35 kc. Over this wide frequency band, many sources of self-noise have areas of dominance.

Much self-noise data refer to hydrophones such as the JP-1 or JT, located topside on the submarine forward of the conning tower. There is ordinarily no dome about the transducer, although it may have a faired strut supporting it above the level of the deck.

In the following discussion, we will treat the manifold origins of submarine self-noise under three categories, just as we have done for surface ships. Propeller noise is the noise which originates at the submarine's screws when the speed is great enough to produce propeller cavitation. Hydrodynamic noise includes all the noise sources which result from the motion of the submarine through the water. Machinery noise is the noise resulting from the propulsion, maneuvering, and auxiliary machinery of the ship.

Propeller Noise - The importance of propeller noise in submarines is limited (much as in surface ships) to the special conditions of high frequencies, high speeds, shallow depth, and stern bearings. Under these conditions, propeller noise manifests itself as the dominant source of noise; otherwise, it is likely to be overridden by one of the other noise sources.

One method, used to some extent during the war, for determining the presence of propeller noise is to shut off the motors while the submarine is under way, and to note the decrease, if any, in self-noise while the boat is coasting. On one ship (SEALION), a reduction (at 24 kc) of 25 db in a QB hydrophone on stopping the motors was found when moving at 9 knots. However, on another submarine, PIPEFISH (SS 388), there was no marked difference in a QJB topside and forward(30). On QUEENFISH (SS 393), there was likewise no marked change in self-noise levels observed in the JP-1 on bearings other than 180° at speeds of 6 and 8 knots in the frequency range 200 to 6000 cps(56). The discordant results may have been due to the hydrophone position, since the hull of the vessel may have shielded the propellers in the last two cases.

Recent trials have shown that the propellers account for the self-noise of the JT equipment on after bearings(57). On POMODON (SS 486) and RONQUIL (SS 396), this noise appeared suddenly as the submarine speed was increased, and was suppressed by submerging to a greater depth; these effects are typical characteristics of propeller cavitation. Other evidences for the existence of propeller noise may be found in the similarity in spectra at high frequencies, and in the similar rate of increase with speed, between the self-noise and the noise radiated to a distance, which is known to be largely propeller noise at high frequencies(30,58). Yet, recent British trials on the submarine SCOTSMAN show that the propeller component of self-noise is dominant only under the conditions of periscope depth and speeds above 12 knots(38).

There is little discussion in the literature as to the paths by which propeller noise reaches a hydrophone (such as the JT) located topside and forward on the boat. Since there would not be a direct line-of-sight path from a hydrophone in this position to the screws, it is likely that reflection from the surface provides a path by which propeller sound reaches a forward hydrophone which has little or no directivity in the vertical plane. The importance of this path in torpedo self-noise is well known. In submarines, it may be equally important for JT hydrophones trained aft at high frequencies.

Hydrodynamic Noise - Under this heading are included for the purpose of discussion all those sources of noise resulting from the flow of water around and past the hydrophone (with its support) and the outer hull structure of the submarine. Hydrodynamic noise includes the turbulent pressures produced upon the hydrophone by flow vortices, the rattles and vibration induced by the flow in the submarine plating and the hydrophone assembly, and even the noise radiated to a distance by vortices. Thus, although hydrodynamic noise has a variety of origins which depend upon particular conditions, all are the result of the motion of the submarine through the water.

The general importance of hydrodynamic noise is well known. It has been demonstrated by self-noise measurements in GRENADIER (SS 525), whose variable-pitch propellers permitted the separation of flow and machinery contributions to self-noise when the vessel was operated at a depth sufficient to prevent cavitation(44). Flow effects near and around the JT hydrophone were found to be major sources of JT self-noise despite the use of a fairing around the hydrophone support. Further confirmation of the importance of these effects has been provided by trials with a streamlined dome around the JT on HALFBEAK (SS 352). In these trials, not yet reported in detail, DTMB found reductions of up to 20 db in self-noise levels(83).

The fact that water flow around the hydrophone itself does sometimes create the major part of self-noise is shown most strikingly by measurements with streamlined and nonstreamlined hydrophones. It was found, for example, as a result of trials in BLUEGILL (SS 242) that low-frequency self-noise due to hydrodynamic noise could, by streamlining a hydrophone, be reduced to the extent that machinery noise predominated at high speeds(59). It was also concluded from these trials that the apparent noise pressures produced by turbulence are in actuality the fluctuating turbulent pressures on the face of the hydrophone, and are created by its presence in the flow stream, rather than by the radiated noise of distant vortices. This was shown by the fact that only the front end of the streamlined fairing was found to be important; the removal of the fairing from the rear was observed to have no effect(59). On the other hand, an example of hydrodynamic noise originating at a distance and picked up by the JT hydrophone may account for the unusually high JT self-noise levels on K-1, where the AN/BQR-4 dome on the bow was suspected of causing additional eddying and turbulence(60).

Another important form of hydrodynamic noise may be said to be the flow-induced vibration of the hydrophone and of the submarine plating in its vicinity. At low frequencies, the JT has been observed to behave as an accelerometer, picking up the rumble of the ship(61). Flow-induced vibration is particularly important in the JT, and undoubtedly accounts for the higher

levels observed with this hydrophone on bow and stern bearings,* when the hydrophone lies across the flow. During postconversion (to SSK class) trials on GROUPER (SS 214), a sharp thumping noise, clearly heard in the forward torpedo room, was produced by the JT mount at a speed of 100 rpm when the JT was trained toward 180° or 000°(62). Similarly, on POMODON (SS 486) at a speed of 150 rpm severe clicks were observed when the JT was trained ahead or aft, giving high noise levels at 000° and 180°, which were attributed to vibration caused by the flow at this speed(57).

That the superstructure and fairwater plating can be excited into vibration, and create higher levels on the JT, was indicated by tests with PICKEREL (SS 524) which resulted in a lower self-noise (by about 7 db) at speeds near 4 knots when the deck plates were painted with a vibration-suppression undercoating(61). On TRUMPETFISH (SS 425) and AMBERJACK (SS 522), additional stiffening of the superstructure and fairwater plating was found to reduce the self-noise in hydrophones located in the superstructure, and the use of wood instead of steel provided some additional noise reduction(63). Finally, tests on GRAMPUS (SS 523) gave evidence that at speeds below 120 rpm in the ultraquiet condition, the vibration of the superstructure plating contributed to the sound field present near the hull(64). These flow-excited vibrations of the submarine superstructure can reach a mounted hydrophone either through its supports or through the water(56).

In short, hydrodynamic noise represents the pressures associated with the random velocities of turbulent flow. These pressures commonly originate (a) at the hydrophone and its support or (b) at structures and plates excited into vibration by the flow(59). Also, the turbulent eddies themselves may act as radiating sources. Hydrodynamic noise probably has a sensibly continuous spectrum, and in this respect it differs most markedly from machinery noise which has a discontinuous spectrum containing line components. However, its spectrum and, indeed, the spectrum of other sources of submarine self-noise, appear not to have been studied to any significant extent.

Machinery Noise - Machinery noises are characterized by the existence of line components which stand out above a continuous background at low frequencies. At somewhat higher frequencies (say, 500 to 1000 cps) the number of line components increases, and they combine with the continuous background to give a nearly uniform spectrum when observed through wide-band filters. As we have seen earlier in the discussion of surface ship self-noise, machinery noise levels are, by contrast with other forms of self-noise, relatively independent of speed. Furthermore, the spectrum level of machinery noise falls more rapidly than that of other forms of self-noise or ambient noise. These characteristics cause the importance of machinery noise to be greatest at low frequencies and low speeds—the conditions of particular importance for submarine listening.

It has long been recognized that machinery noise is important under these conditions. It has been reported, for example, that in wartime JP equipment at speeds below about 5 knots, listening was not affected by turbulence or propeller noise; the noise from power operation of the bow planes, stern planes, steering machinery, and from certain rotating equipment within the submarine was of greater significance(65, p. 108). Many more recent investigations have confirmed the importance of machinery noise at low speeds and frequencies, even when only a minimum of auxiliaries are allowed, as in the ultraquiet condition(44,59,66). Because of the inevitable presence of noisy auxiliary machinery, self-noise levels lower than the levels of the Knudsen curve for sea state 2 (Fig. 1) are never observed on submarines at frequencies below 1 kc in sea state 0 or 1, even when the submarine stops, balances on a density layer, and secures all unnecessary auxiliary machinery(44,63,67,68). Although machinery noise is usually of minor importance at high frequencies, noisy auxiliaries may be as troublesome at 24 kc as on surface ships. It was found in wartime tests on SHARK (SS 314), for example, that the self-noise on one bearing was increased by 20 db by a noisy compressor(30).

Of all the noise-producing machinery in submarines, particular attention has been paid to the auxiliaries because of their importance in the ultraquiet condition. Some particularly noisy

*See Figure 22

auxiliaries(5, p. 231) such as trim and bilge pumps(59), bow and stern planes operated on power(62), etc., are operated only intermittently, and, regardless of their level, probably do not significantly affect detection. Yet, there are many noisy auxiliaries whose continued operation is necessary or desirable for the operation and habitability of the vessel. For example, at low frequencies in BLUEGILL (SS 242), the chief offenders were the air-conditioning and refrigeration equipment, which were noisier than any other piece of machinery (including the main propulsion motors) and which raised the self-noise level some 10 to 15 db above the ship's ultraquiet noise level with only the I.C. generator operating(59). On the submarine K-1, a band of line detail near 890 cps appeared in the spectrum of JT self-noise which was believed to be amplidyne or synchronoise(60). In earlier listening tests, too, JT synchronoise was found to be troublesome, and it was concluded that training the JT by hand, with power secured, was necessary to pick up targets which would otherwise be undetected(69).

The conditions of operation of auxiliary machinery aboard submarines are indicated by various terms (such as, ultraquiet, patrol-quiet, etc.) to indicate the particular degree of noise quieting of the ship and the different auxiliaries which are operative. Table 4 is a general guide to the machinery which is operating or nonoperating in the patrol-quiet and ultraquiet conditions.

TABLE 4‡
Quiet-Condition Guide—Submarine ASW Manual, NWIP 23-4, Office of CNO, 1953

In Use	Ultraquiet*	Patrol-Quiet†
Bow planes	Hand	Hand or emergency
Stern planes	Hand	Hand or emergency
Steering	Hand	Power motors secured, except when needed
Master gyro	On	On
I.C.M.G. (Numbers)	1	As necessary
Battery vent blowers	1 per battery (slow)	1 per battery (slow)
Hull vent blowers	Off	Slow
Refrigeration plant	Off	On
Air-conditioning plant	Off	1 plant
Circulating water pump	Off	As necessary
Hydraulic plant	Off	On
Propulsion	Off	As necessary
Sound gear	JT (hand train when practicable)	JT (others as necessary)

*Ultraquiet—Maximum silencing of ship's noise to obtain extreme listening range, or for determination of noise levels.
†Patrol-Quiet—Quietening the ship to the maximum possible extent, consistent with normal living. This is the usual quiet condition while in the patrol area.
‡The accompanying table is a recommended guide to follow when setting the two quiet conditions. It has been found that the machinery of certain ships will vary in sound emission, and that certain individual modifications to this recommended list may have to be made. For example, two I.C. motor generators at half load are often quieter than one at full load. The decision as to whether or not to run a particular piece of equipment can only be made by analysis of sound tests and observations. Each ship should prepare standard shipboard bills detailing what equipment is to be secured during each quiet condition. These bills should be posted in every compartment, and the same discipline should be exercised in enforcing them as in enforcing other ship's bills.

Most recent self-noise data have been obtained with the minimum of auxiliaries operating, that is, in the ultraquiet condition. Self-noise levels were compared at NEL for the various conditions of GROUPER (SS 214), both before and after conversion to SSK, when particular attention was paid to the noise problem (62, 66). Surprisingly, both before and after conversion, no difference in level was observed when the vessel was operated in the different conditions. After conversion, this may have been due to one auxiliary (a gyro synchro amplifier located in the forward room) which produced considerable airborne hum, but which was considered so insignificant as not to be listed as ultraquiet machinery (66). This result emphasizes the importance of the path between a noise source and the hydrophone in determining its importance to self-noise (66).

The main motors and associated propulsion plant undoubtedly contribute to self-noise at low frequencies. In particular, line components due to main motor slot noise may occur, although these may be reduced by the use of skew slots(44). Some increase in level does occur at low frequencies on starting the motors(44,59); it was found that in the fleet submarine BLUEGILL (SS 242), known to be noisy because of its gear drive, the levels with the main motors running were some 6 db below those due to the refrigeration and air-conditioning systems(59). DTMB trials in GRENADIER (SS 525), which was fitted with variable-pitch propellers, also suggest that noise due to the main motors and associated plant may be of minor importance. These trials were conducted in the ultraquiet condition at a sufficient depth to prevent cavitation at the propellers, so that it was possible to differentiate between the sources of noise on a basis of whether the noise level varied with speed through the water or with propeller rpm. Self-noise measurements were made in the JT and various hydrophones along the vessel. Propulsion plant noise was found to be important only in hydrophones near the propeller, and even then only in half-octave bands covering the frequency range 1430-5700 cps when the vessel operated at speeds in excess of 4.5 knots(44).

One series of self-noise measurements indicate the increased levels to be expected from main engine operation in a snorkelling vessel, the K-1 (SSK-1). Although the self-noise levels at high speeds were about the same as for battery motor drive, the levels for snorkel operation, as the speed was reduced from 8 knots, exceeded those for battery operation by the increasing amounts of 2-4 db at 6 knots, 5 db at 4 knots, and 4-7 db at 2 knots. The high levels were most noticeable in the frequency range 0.5 to 1 kc and 4-10 kc(60). It is of interest to note that the use of sound isolation mounts under the diesels on K-1 (SSK-1) reduced self-noise ordinarily transmitted via the bed plate to the hull(70). No improvement was observed in the JT self-noise at high speeds where flow noise and turbulence effects accounted for the self-noise(70). At 2 knots, the levels for the line components in the frequency range 30 to 150 cps were increased by 10-15 db, and, for the continuous spectrum between 300 and 2000 cps, by 5-10 db, when the mounts were shorted out. This result appears to contradict the radiated noise measurements on K-2 (SSK-2), conducted by NEL, which showed no significant differences in radiated noise levels for the vessel with and without mounts(71).

Little is known about how machinery noise is transmitted to a hydrophone mounted topside and forward in the boat. Two available paths are (1) direct transmission through the hull to the hydrophone support and, (2) radiation from the hull into the water and thence, by a water path, to the hydrophone. Wartime experience with the JP-1 equipment showed that shock-mounting the hydrophone reduced the levels by about 3 db in the frequency range 1-3 kc at speeds of less than 4 knots and possibly by more at lower frequencies, indicating that an appreciable portion of the self-noise was due to transmission through the support(30). Although the JP-1's postwar

counterpart, the JT, includes certain sound and vibration isolation features, rigidity considerations necessitate that these be limited(44). Transmission via the support still contributes to the self-noise level. For example, measurements on the K-1 showed a band of line detail, due to amplidyne or synchro noise which must have been transmitted via the JT training shaft, since it was not heard on a nearby OMA hydrophone(60).

Tests of the USL pressure gradient hydrophone on HALFBEAK with and without vibration isolation have shown that both the waterborne and the hull-transmitted paths are of importance for machinery noise(72). Narrow-band analysis of the noise in the frequency range 50 to 1000 cps showed that some line components were reduced in level by the use of isolation, while others were not, probably depending on the path involved. On the other hand, MPL has found on BLACKFIN (SS 322), that wrapping a hydrophone in corprene reduced the noise level by about 20 db at frequencies of the order of 100 cps, indicating that transmission via the support was negligible(73).

It should be emphasized that most submarine self-noise data has been obtained in terms of half- or third-octave band levels, which must then be expressed in terms of spectrum levels. Such measurements deemphasize the line components in the background, and thus apparently diminish the importance of machinery noise. Great care is necessary, therefore, in interpreting such levels as background levels for use in narrow-band systems. For example, a narrow-band analysis of the self-noise in the topside JT on the postconversion GROUPER (SSK 214) revealed considerable line detail, especially near 360 cps, where the masking threshold* was raised about 13 db as compared with the adjacent continuous background(66). This could not have been deduced from the half-octave band data for this vessel(62).

<u>Relative Importance of the Sources of Noise</u> - The relative importance of the self-noise sources we have been discussing depends upon many factors. Two of the most important determinants of their relative importance are the speed of the submarine and the frequency at which the noise is observed. Figure 15 is an attempt to indicate the areas of dominance of the various sources of noise on submarines as a function of these variables. The outstanding features of this figure are somewhat as follows.

Consider first what occurs at low frequencies at, say 100 cps. There, both auxiliary machinery and hydrodynamic noise are the principal sources. Their relative importance depends upon speed and upon whether narrow or wide frequency bands are used in the noise measurement. As the speed increases, the hydrodynamic noise gradually overwhelms the noise from the auxiliary machinery which tends to remain independent of speed.

The situation is completely different at high frequencies. At, say 20 kc, the principal source of noise is the ambient noise of the sea at slow speeds, and propeller noise at high speeds; the former yields to the latter rather suddenly at the speed at which propeller cavitation occurs. At intermediate frequencies, say in the decade 1 to 10 kc, there are many areas in speed and frequency at which two or more sources may be equally important. In this frequency range, too, the peculiar conditions of the individual submarine are apt to determine the individual source importance.

Other factors besides speed and frequency may affect the relative importance of the noise sources. For example, propeller noise diminishes with increasing depth, or is enhanced by a nicked or damaged propeller. Some of these effects will be indicated in the following paragraphs.

*That is, the level as measured in a 50-cps band—the aural critical bandwidth.

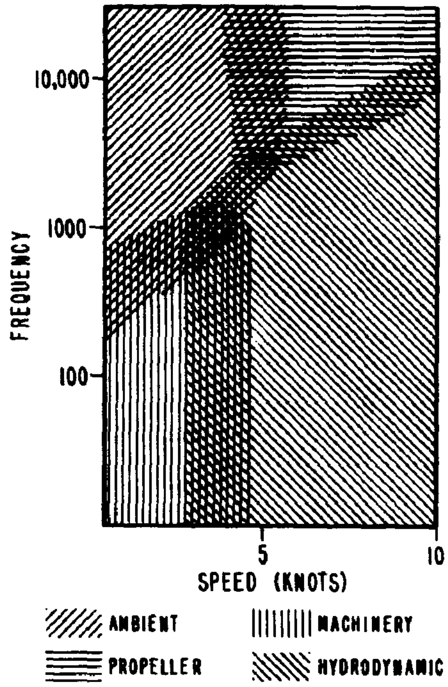
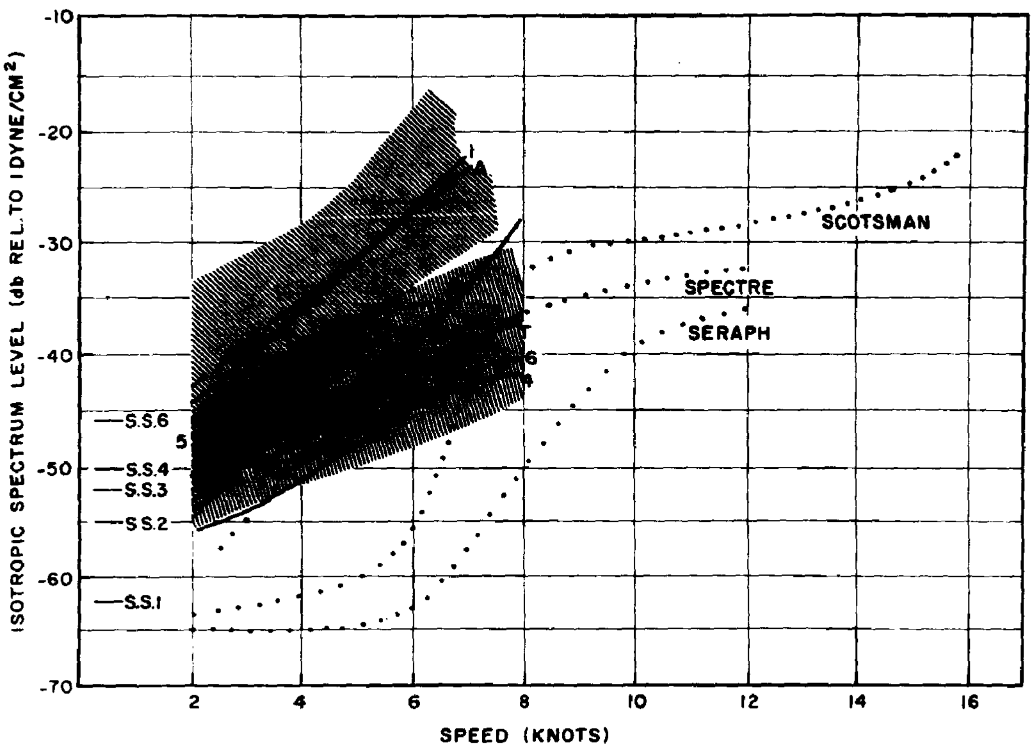


Figure 15 - Diagram showing the importance of the various sources of submarine self-noise at different frequencies and speeds for a forward topside hydrophone at periscope depth

Self-Noise Levels

Effect of Speed - Just as for surface ships, the variation of self-noise with the speed of the boat has received considerable attention in the literature. The subject is made more complicated than on surface ships, however, by the wide frequency range of concern in submarine sonar, and by the fact that the depth of the submarine is an additional variable.

At high frequencies, if propeller cavitation occurs, the self-noise vs. speed curve has a shape like the letter S; this is a diagnostic characteristic of propeller noise. At speeds below the onset of cavitation there is little or no rise above ambient level; as the speed is increased there is a sharp rise in level at the speed where cavitation first occurs, followed by a slower rise at the higher speeds. The effect of a greater depth of submergence is to delay the onset of cavitation, and to shift the S-curve toward the higher speeds. The characteristic S-shaped curve was indicated long ago by wartime measurements at 17 and 24 kc on QB and JK transducers(30), although the inflection point of the curve appears not to have been reached for some of the submarines studied. A more recent example of this behavior occurred at 24 kc with the NRL XDG transducer (searchlight-type in a cylindrical dome with a hemispherical cap), which showed an increase of level of only 4 db between zero and 4 knots and a rise of 8 to 10 db between 4 and 5-1/2 knots at periscope depth(74). Other examples of the S-shape (Fig. 16) are evident in the results of British measurements with 10-kc searchlight transducers of Type-129 equipment installed in various submarines(58).



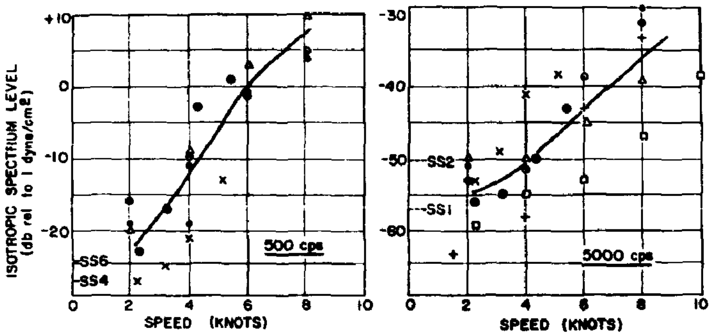
			length	beam	draft
	A : British "A" Class,	average and spread, 7 ships	281-2/3'	22-1/4'	17'
	T : " "T" "	average and spread, 6 ships	273'	28-1/2'	12'
......	: " "S" "	modified for high speed	217'	23-3/4'	10-1/2'
——	1,2 : " "S" "		217'	23-3/4'	10-1/2'
——	3 : " "U" "				
——	4 : " P 211				
——	5 : Russian "L15"		279'	23'	16-1/2'
——	6 : Turkish "ORUC REIS"	British built	201'	22-1/3'	10-1/2'

Figure 16 - Self-noise levels observed in British type 129 equipment at 10 kc (directivity index 18 db) on forward bearings at periscope depth (Ref. 58)

When hydrodynamic noise is dominant, as at the lower frequencies, one might expect the increase of noise level with speed to be more nearly linear than when propeller noise is dominant.* Plots of isotropic self-noise levels in JT hydrophones at 500 and 5000 cps presented in Fig. 17 tend to confirm this opinion. The slope of the mean curve at the lower frequency (about 5 db per knot) is greater than that at the higher frequency (3 db per knot). Wartime measurements with the JP-1 hydrophone also showed a greater rate of increase of self-noise with speed at frequencies below 1 kc although the rate of increase in the decade 1-10 kc appeared to be independent of frequency(30).

Table 5 presents data on the average variation of self-noise observed in four equipments on submarines operating at periscope depth at speeds from 2 to 8 knots. The agreement

*Cf. surface ship self-noise versus speed, Fig. 12.



Symbol	Operation	Ship	Lab.	Ref.	Remarks
●	Battery	K-1 (SSK 1)	USNUSL	60, Fig. 5	Train 270; patrol quiet, keel depth 45'
●	Snorkel	K-1 (SSK 1)	"	60, Fig. 6	Train 270; patrol quiet, keel depth 45'
△	Battery	Grenadier, SS525 (Guppy II Class)	DTMB	44, Fig. 8	Actual measured frequency of 5000 cps points: 5700 cps; 500 cps points are mean values between 360 and 715 cps reported measurements; depth 400'; ultra quiet conditions, train angle 000 (not beam bearings). Steel fairing fitted over discontinuities in JT baffle assembly.
□	Battery	POMODON, (SS 486) (Guppy, no Snorkel)	NEL	57, Fig. 13	Average of 60, 100, and 200' keel depths; plotted points are mean of 3.7 and 6.7 kc reported values; Train angle 270, silent condition.
+	Battery	RONQUIL (SS 396) (Fleet Type)	NEL	57, Fig. 14	Plotted points mean of 3.9 and 7.2 kc reported values; Average of 3 keel depths as above; train angle 270. Silent condition
x	Battery	GROUPER (SS 214) (Fleet Type) preconversion	NEL	62, Fig. 5	Measurements reported in half-octave bands; keel depth 55-60; angle 90 and 270 averaged. Various conditions
●	Battery	GROUPER Postconversion to (SSK 214)	NEL	62, Fig. 8	Same, but train angle 90°; top-side hydrophone. All conditions, "ultra quiet" to "in transit."

Figure 17 - Self-noise levels in the JT hydrophone at 500 and 5000 cps at different speeds, and at periscope depth, with the JT trained to beam bearings, except in one instance. JT directivity index is assumed to be 1 db at 500 cps and 11 db at 5000 cps for the reduction to isotropic levels. (Ref. 76, Fig. 5)

between the four systems is surprising in view of the differences in hydrophone type, frequency, and probable source of the self-noise. In particular, it emphasizes the difficulty in deciding which is the prominent source of noise from self-noise vs. speed curves alone.

In contrast to the self-noise vs. speed curves of the JT equipment (which show considerable change with speed even at 2 knots), measurements on other hydrophones have shown no change in level up to speeds as high as 4 knots. Such results were obtained with hydrophones and accelerometers installed in the forward superstructure and conning tower of AMBERJACK (SS 522), and TRUMPETFISH (SS 425)(63), and also in forward hydrophones on the GRENADIER (SS 525). In GRENADIER these levels approximated the level of ambient noise in sea state 2, and were attributed to ambient and auxiliary machinery noise(44).

We have mentioned, when discussing machinery noise as a contributor to self-noise in submarines, that the minimum levels attainable at low frequencies approximate the Knudsen ambient-noise curve for sea state 2, even when the ship is in the ultraquiet condition and is hovering on a density layer. At high frequencies, self-noise data for the JT equipment (Fig. 17), similar data for the British Type-129 equipment (Fig. 16), and wartime data for QB, JK,

TABLE 5
Increase of Self-Noise With Speed Over 2 Knots Observed in Various Equipments on Submarines at Periscope Depth

System	Frequency (kc)	No. of Vessels	Isotropic Self-Noise Level (db) Relative to That at 2 Knots			Reference
			4 Knots	6 Knots	8 Knots	
JT	5	5 (One vessel at 400')	4	12	19	Fig. 17
JP-1	1-10	8	3	10	22	30, Fig. 15
QB, QJB, or JK	17 & 24	5	2	11	26	30, Figs. 31 & 32
British Type 129	10	22	4	11	19	Fig. 16

and JP-1 hydrophones, given later in this summary(30),* indicate that at low speeds ambient noise may be the dominant background. Reference to the various figures shows, however, that levels considerably higher than ambient are sometimes observed under these conditions. A further exception was found with the NRL 10-kc echo-ranging system installed on GUAVINA (SS 362), at a location forward and topside on the boat, where the self-noise at 1.9 knots was 5 db above calculated ambient levels for sea state 2(75).

Spectrum of Submarine Self-Noise - The spectrum of self-noise on submarines depends upon which of the three principal sources of noise is the dominant one under the particular conditions and in the frequency range of interest. Machinery noise has a spectrum of line components, of irregular amplitude and more or less regular spacing, having an envelope which falls rapidly with increasing frequency above 1 kc, possibly by 12 db per octave. The spectrum of the noise from propeller cavitation, like that of deep-water ambient noise, is continuous, and falls at a rate of approximately 6 db per octave. The spectrum of hydrodynamic noise is also continuous, and undoubtedly falls more rapidly with frequency than that of propeller noise, and probably less rapidly than machinery noise. Wartime measurements on the JP-1 hydrophone(30), together with the data reported below for the JT hydrophone, suggest that the frequency dependence of hydrodynamic noise is at least 9 db per octave and is possibly as high as 12 db per octave. Both machinery noise and hydrodynamic noise spectra are of a high level at low frequencies and fall below propeller noise at high frequencies. Some indication of the relative slopes and levels of the various components of self-noise, when auxiliary machinery is operating and when propeller cavitation occurs, is given in Fig. 18. Undoubtedly, the situation varies from ship to ship, even when operated in the same condition.

A compilation of measured JT self-noise spectra obtained from postwar sources is shown in Fig. 19 for speeds of 0.9-2.5 knots and 8 knots. It should be noted that the spectra are plotted as isotropic levels, obtained by applying the directivity index of the JT hydrophone, shown in the lower part of the figure, to the reported plane-wave levels. The slope of these spectra is seen to be less at high frequencies than at low, in agreement with

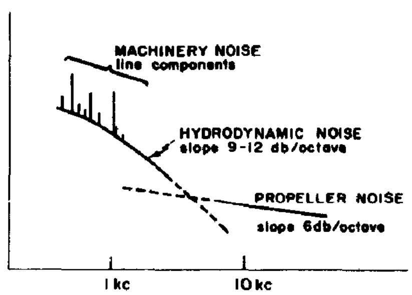
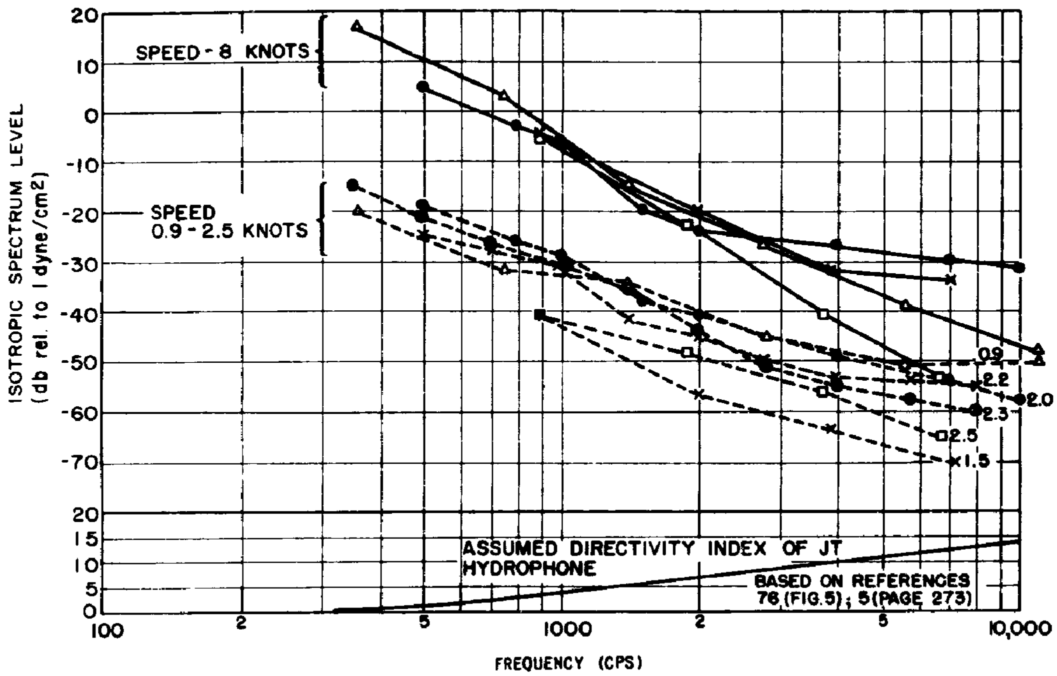


Figure 18 - Relation between the spectra of the various components of self-noise in JT hydrophones

*See Fig. 20.



Symbol	Operation	Ship	Lab.	Ref.	Remarks
•	Battery	K-1 (SSK 1)	USNUSL	60, Fig. 5	Train angle 270; patrol quiet. Keel depth 45'
⊖	Snorkel	K-1 (SSK 1)	USNUSL	60, Fig. 6	Train angle 270; patrol quiet. Keel depth 45'
△	Battery	GRENADIER (SS 525) (Guppy, II Class)	DTMB	44, Fig. 8	Train angle 000; depth 400' ultra quiet; no cavitation
□	Battery	POMODON (SS 988) (Guppy, no Snorkel)	NEL	57, Fig. 13	Train angle 270; average 80, 100 and 200' depths. Silent condition
+	Battery	RONQUIL (SS 396) (Fleet Type)	NEL	57, Fig. 14	As above.
×	Battery	GROUPER (SS 214) (preconversion)	NEL	62, Fig. 5	Train angle 90 and 270; keel depth 55-60'
●	Battery	GROUPER (SS 214) (postconversion)	NEL	62, Fig. 8	As above

Figure 19 - Spectra of JT self-noise at two different speeds, converted to isotropic levels by applying the directivity index according to the lowermost curve. For beam bearings, except in one case, see remarks.

what one would expect from the general considerations of the preceding paragraph. Values below about 500 cps are somewhat—perhaps seriously—in error because of the customary practice of using fractional-octave bandwidths in making the self-noise measurements.

The average, and upper and lower limits of the JT self-noise data, for the lower speed given in Fig. 19, have been replotted in Fig. 20 for comparison with earlier wartime data on the JP-1 hydrophone(30). Also included is a curve showing the average spectrum of self-noise observed in wartime directional equipments in the frequency range 10-40 kc(30). Here (as with the JP-1 hydrophone), the levels varied by as much as 30 db from vessel to vessel. These curves clearly show the wide spread in submarine self-noise data. On the average, the JT on beam bearings is quieter than the JP-1, although its spectrum is remarkably similar.

Although the spectra plotted in Fig. 20 refer to a speed of 2 knots, the spectra at higher speeds for frequencies above 1 kc are similar. It has been indicated, for example, that at speeds higher than 2 knots for the JP-1 hydrophone in the frequency range 1-10 kc, and for the QB, QJB, and JK hydrophones, the levels may be obtained by adding to the 2-knot levels an amount independent of frequency(30).* We have seen earlier, when discussing the effect of speed on self-noise, that the levels below 1 kc increase more rapidly with speed than at higher frequencies.

Effect of Depth - The operating depth of a submarine affects its self-noise principally by suppressing propeller cavitation. This effect of depth is most apparent at high frequencies and on the stern bearings of a directional hydrophone. An increased depth increases the speed at which the sharp rise of noise with speed occurs. These effects seem to have been recognized(5,30) during the war, and have been confirmed by more recent measurements of JT self-noise(57) on POMODON (SS 486) and RONQUIL (SS 396). When these vessels were operated at 40 rpm (2 knots), most of the excess noise at stern bearings (believed to have been due to propeller cavitation) was suppressed at a keel depth of 100 feet; at speeds above 4 knots (Fig. 21) most of the excess noise on stern bearings at high frequencies was suppressed at a 200-foot keel depth. At these speeds, however, some excess noise remained on stern bearings as compared with beam bearings; the levels on forward bearings were also high. These higher levels on bow and stern were believed to have been due to the vibration of the hydrophone and to the turbulence around it. The excess on bow bearings was also somewhat affected by depth (Fig. 21), which may have indicated cavitation around the hydrophone(57).

However, depth has little effect on self-noise when cavitation (whether at the propellers or at the hydrophone face or its surroundings) plays no part in producing observed self-noise. At low speeds and low frequencies, therefore, self-noise is sensibly independent of operating depth.

Effect of Hydrophone Train Angle – As a result of the limited data obtained with JP-1 hydrophones during the war, it was concluded that if there were any prevalent directivity to the sonic self-noise on submarines, it was neither conspicuous nor reliable (30). There was some evidence, however, that at higher speeds (6 knots) and frequencies (above 3 kc), the levels on stern bearings were 6 db or more higher than those in other directions (56). More recent data on the variations of self-noise with bearing as observed in JT hydrophones do show some direction effects, even at stern bearings.

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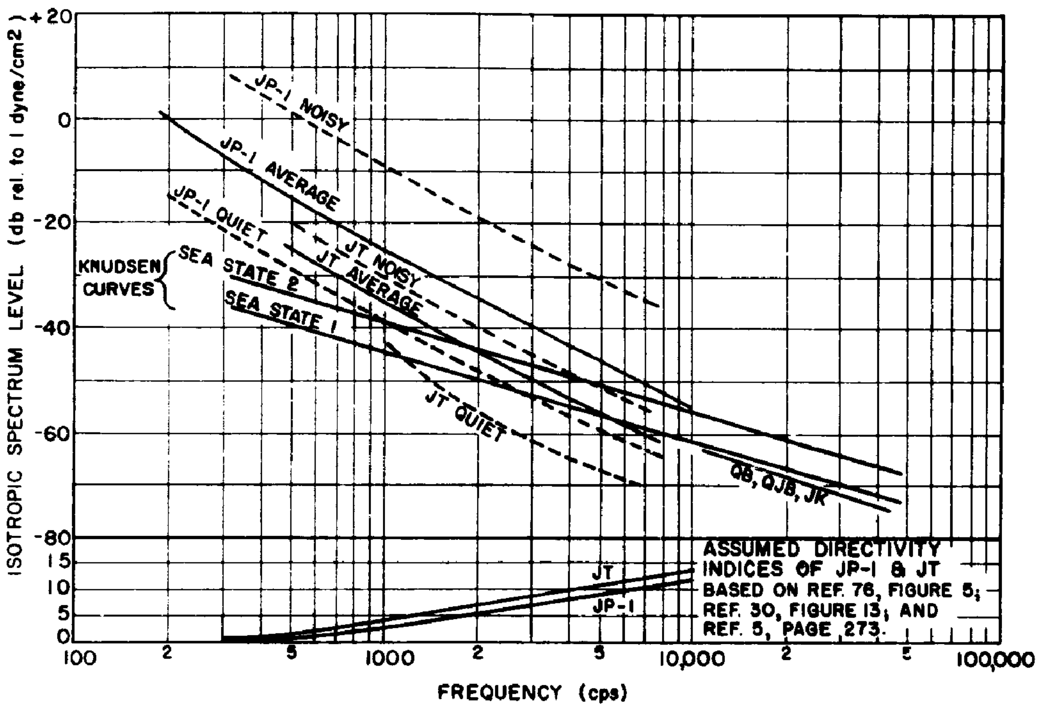
*See Table 5



System	Average of:	Reference	Remarks
JP-1 hydrophone	8 vessels	30 (Figs. 12 and 13) 56 (Fig. 17)	Train 000, 090 & 270
"Supersonic" self-noise, QB, QJB or JK directional hydrophones	5 vessels	30 (Figs. 23 and 25)	Train 045
JT hydrophone	5 vessels (one vessel, depth 400' and train 000)	Based on Fig. 18, this report	Train 090 or 270

Figure 20 - Average spectrum level of self-noise in various sonar systems on submarines operating at a speed of 2 knots at periscope depth

The variation of self-noise with train angle as observed in JT hydrophones by various observers on four submarines is shown in Fig. 22. The four directional patterns are for different combinations of speed and frequency. Data for each condition and for each ship have been normalized to zero db at 090° so as to facilitate comparison. Some general features of these polar plots are evident. First, the quietest position of the JT is seen to be at beam bearings (090° and 270°). Second, at the lower frequency and at the lower speed (where the directionality of the hydrophone is small and where there is no cavitation) the patterns are nearly circular. At the higher speed, both the low- and high-frequency levels are usually high on forward bearings. This, as we have seen earlier, has been attributed to flow-generated vibration of the hydrophone, which would be greatest when the hydrophone length is across the direction of ship movement(57). The high levels on stern bearings at the higher frequency are undoubtedly due to propeller noise in some cases, as in POMODON (SS 486) and RONQUIL (SS 396) where these levels decreased on submerging(57). In the post-conversion GROUPER (SSK 214), however, the bottomside JT self-noise levels were essentially independent of train angle(62), in contrast to the levels for the topside JT shown in Fig. 22. This difference suggested that the superstructure was the source of the high level in the topside JT when trained aft, rather than the screws.

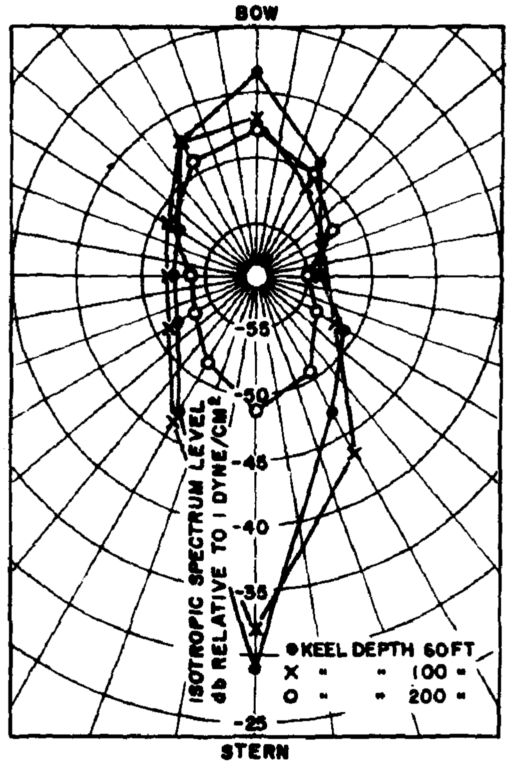
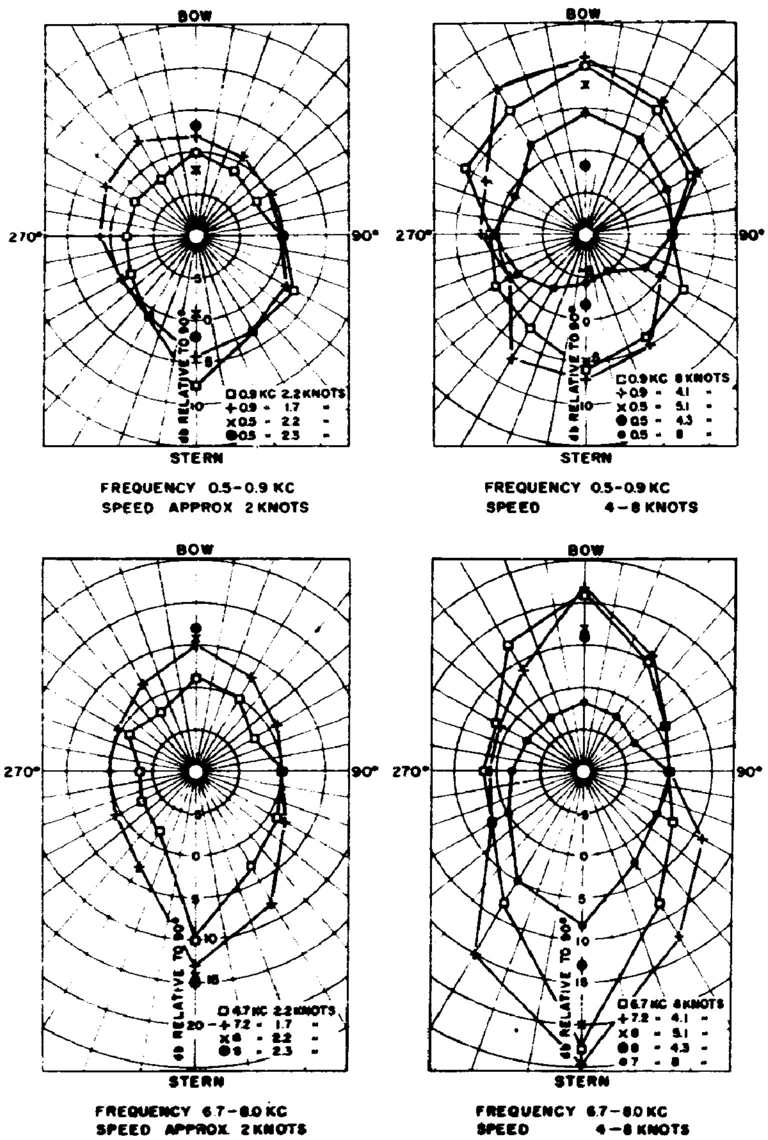


Figure 21 - Effect of depth on submarine self-noise at various bearings. Data are for the JT equipment on POMODON (SS 486), a guppy submarine without snorkel, speed 8 knots. Frequency is 6.7 kc, assumed directivity index is 12 db. (NEL data from Ref. 57, Fig. 17)

Observations of the directional properties of self-noise at higher than sonic frequencies in submarines appear to be limited to wartime data obtained with QB and JK hydrophones. For submarines at speeds up to about 6 knots, the self-noise at frequencies between 15 and 35 kc was found to be independent of bearing, except for an arc 45° on either side of the stern(30) where the levels were 10 to 30 db higher than on other bearings. In addition to the stern peak, local peaks occurred when directed toward a source of noise. On PIKEFISH, such peaks were found in the direction of the JP training gear, the conning tower, and other imperfections in the deck(30).

Effect of Hydrophone Location - The most nearly systematic study of the effect of location of the hydrophone along the boat on self-noise levels was made by DTMB(44,67) on GRENADIER (SS 525). Hydrophones and accelerometers were placed at various "test positions" forward in the vicinity of the JT, inside the conning tower fairing, and near the stern above the propellers. Surprisingly enough, less noise was found near the screws than in the forward superstructure



□ POMODON, SS 486, guppy without snorkel, keel depth 60 ft, NEL data, Ref. 57, Fig. 17

+ RONQUIL, SS 396, fleet type without guns and life lines, keel depth 60 ft, NEL data, Ref. 57, Fig. 18

× GROUPER, SS 214, fleet type, preconversion, keel depth 55-60 ft, NEL data, Ref. 62, Figs. 5 and 6

● GROUPER, SSK 214, after conversion to SSK, topside unit, keel depth 55-60 ft, NEL data, Ref. 62, Figs. 8 and 10

• K1, SSK 1, keel depth 45 ft, USL data, Ref. 60, Fig. 8

Figure 22 - Directional characteristics of JT self-noise at two frequencies and two speeds for battery-driven submarines at periscope depth

when measured below 600 cps at speeds between 5 and 15 knots; this was attributed to flow-induced vibration, together with turbulence in and around the forward superstructure, picked up by a forward hydrophone. The low-frequency noise in a hydrophone near the propellers was found to depend on the rpm of the screws rather than on the forward speed of the boat, varying as the 7th power of the rpm between 100 and 800 cps when the propellers were not cavitating; this noise was independent of the pitch of propellers and the depth of the boat.

Another comparison of hydrophones in different locations was made on the converted GROUPER, which had a bottom-mounted JT as well as the topside JT(62). The bottom unit was quieter by 10 db than the topside JT at 8 kc, 180° train angle, and a speed of 2 knots, although there was no difference at 1 kc and below. The low-frequency AN/BQR-2 array on this vessel gave no material decrease in detection performance in sea states 1 to 2 on going from the ultraquiet to the patrol-quiet conditions at 1/3 or 2/3 speed(76); this was believed to have been due to the forward location of the array at the bow, where water turbulence was slight. On the other hand, the BQR-4 array around the conning tower was sensitive to the operating condition of the boat's auxiliary machinery, giving considerable reductions in detection range under other than ultraquiet conditions.

A third instance of a comparison between units was afforded by NRL trials on SEACAT of the experimental XDG equipment, which had two searchlight transducers in domes, one forward and one aft over the screws(74); the after transducer, at 24 kc, was 12 db noisier than the forward one, as one might expect, at aspects other than 180° under conditions of propeller cavitation.

SELF-NOISE IN TORPEDOES

The transducers employed in acoustic homing torpedoes are located in and near the nose of the torpedo. Even in this position they are still not completely isolated acoustically from the principal noise sources—the propellers and propulsion machinery—but are influenced by self-noise that forms the limiting background for passive acoustic homing.

The important sources of torpedo self-noise, and the paths from the source by which the noise reaches the transducers, are comparatively well known for the high frequencies used in acoustic homing. Figure 23 illustrates the paths by which sound originating by cavitation at and near the propellers can reach the hydrophones located at the nose. In addition, local

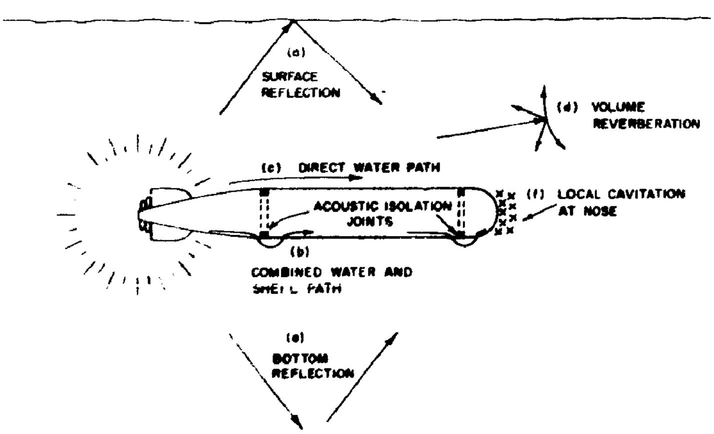


Figure 23 - Origin and paths of torpedo self-noise (copied from Ref. 77)

cavitation at the nose may be the important noise source for high-speed torpedoes running at shallow depths. The relative importance of the paths shown in Fig. 23 is indicated briefly in Table 6. An impressive body of evidence exists to indicate that the surface-reflected path is the dominant one under ordinary conditions of torpedo usage.

TABLE 6
The Paths of Self-Noise in Torpedoes

Path in Figure 23	Relative Importance
a Surface reflection	The most important path for obliquely upward or forward-facing hydrophones.
b Paths lying in part within the torpedo body	Usually rendered unimportant by acoustic isolation joints.
c Direct water path	Shadowing by the torpedo body is effective in reducing this path.
d Volume reverberation	Not usually of any importance.
e Bottom reflection	Unimportant in deep water. Is dominant in shallow water for downward-facing hydrophones.
f Local cavitation	Cavitation should not take place except for torpedoes with the combination of high speed, poor water flow lines, and shallow running depth.

In discussing torpedo self-noise, it is convenient to refer self-, or "internal," noise levels to the radiated, or "external," noise levels of the torpedo. That is to say, rather than to give self-noise levels in absolute units, it is more feasible in order to show the principles involved, to use the radiated noise levels as a reference, and to express the self-noise as a certain ratio of the radiated noise level. This ratio has been called, in a comprehensive report on torpedo noise(77), the front-to-back discrimination (abbreviated FTBD), and is computed in the following way. Referring to Fig. 24, let us imagine that the source of radiated noise of the torpedo—assumed to be located at, or close to, the propellers—is detached from the torpedo and placed on the hydrophone axis at the same distance L from the hydrophone. In other words, an isotropic noise source of the same source level as the torpedo is imagined to be located on the hydrophone axis at a distance L equal to that between the hydrophone and the propellers. Then FTBD is defined to be the ratio in db between the hydrophone response in this fictitious condition to that while the torpedo is running. FTBD is thus the ratio of external to internal noise levels computed as indicated in Fig. 24; like directivity index, FTBD is a positive quantity. It is apparent that FTBD is a result of the shadowing effect of the torpedo body and the directivity of the internally mounted hydrophone.

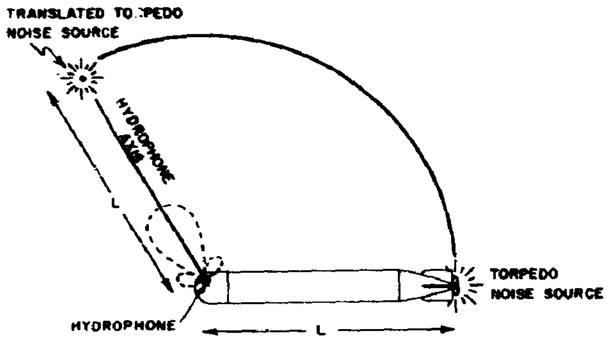


Figure 24 - Diagram illustrating the definition of FTBD (copied from Ref. 77)

Observations indicate for most torpedoes the propeller cavitation is the principal source of self-noise. Recent measurements of self-noise of the Mk 37 torpedo show a good correlation between self-noise levels and the tip cavitation index of the counter-rotating propellers(78), just as for radiated noise. (Cases where nose cavitation exists are of unusual occurrence, as indicated in Table 6.) The use of FTBD rather than the absolute self-noise levels themselves has particular merit for the torpedo engineer engaged in internal-noise quieting, and provides great simplification in discussing torpedo self-noise, since many variables, such as speed, affect both alike.

To convert FTBD to absolute levels, it is necessary to refer to the radiated levels of the torpedo (Part VI of this series). Thus, in using the sonar equations (Part I) for problems involving torpedo self-noise, we must replace the terms N-D (where N is the equivalent isotropic self-noise level, and D the directivity index), by the pair S-FTBD, where S is the radiated level of the torpedo.

FTBD will obviously depend upon the type of torpedo, the acoustic isolation used in its construction, and the type and orientation of transducer used. In what follows, some values of FTBD will be given for the few torpedoes which have been studied exhaustively.

Effect of Speed - Because of the way in which it is defined, FTBD does not normally vary with torpedo speed. This has been demonstrated by postwar measurements on a Mk 20 torpedo in the range 24-36 knots(79). Over great ranges in speed, however, the external and internal noise of a torpedo may not have the same origin, and this lack of dependence on speed of FTBD would not occur. It was found by the British at TEE(80), for example, that at slow speeds before propeller cavitation took place, the principal source of self-noise was the flow of water over the transducer face, while at high speeds, nose cavitation occurred. In such unusual instances, the external and internal noise levels are no longer proportional, and FTBD is speed-dependent. Oscillograms also show that, under certain circumstances, self-noise has a different character from radiated noise, containing sharp "spikes" whose origin is as yet uncertain(80). In the torpedoes, Mk 34, Mk 27, Mk 28, and the British Mk VIII, the slope of the self-noise curve averaged 1 db per knot at 25 kc when measured data on these torpedoes were plotted(81).

Effect of Running Depth - Figure 25 shows FTBD for three torpedoes as a function of running depth below the surface. It is seen that FTBD becomes greater as the depth increases. This can be accounted for on the theory that surface reflection and scattering of propeller noise is the principal source of received self-noise; as the running depth becomes greater, the surface-reflected propeller noise arrives at a more favorable angle for reception in forward- or upward-facing hydrophones.

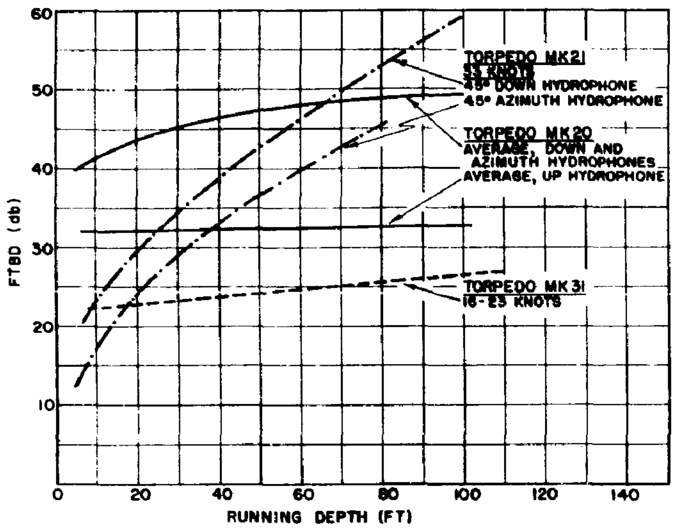


Figure 25 - Variation of FTBD with running depth for three torpedoes. Frequency is 25 kc. (Ref. 77)

The greater FTBD with increasing depth indicates that self-noise levels decrease as the depth becomes greater. The rate of decrease with depth has been estimated to be about 1 db per 10 feet increment of depth when machinery noise is dominant, as in torpedoes without acoustic protection against shell-borne noise, and 1 to 6 db per 10 feet when propeller or nose cavitation is the principal source(81).

The large differences in FTBD among the various torpedoes and hydrophones are the result of different directivities, hydrophone orientations, and differing contributions of nonsurface reflected paths to the self-noise level. For torpedoes in which acoustic isolation is provided in the water-shell path, and in which surface reflection is the predominant path, theoretical computations appear to give good agreement with observations for the FTBD of upward-facing hydrophones, especially when the simple surface-reflection theory is modified to include scattering from the rough ocean surface as well as specular reflection(77). The distribution in angle of surface-scattered sound is a subject important to torpedo homing as well as to many other applications of underwater sound that has not had the study its importance deserves.

Effect of Hydrophone Location - Torpedo self-noise might accordingly be expected to depend upon the orientation, especially in the vertical plane, of the receiving hydrophone. Self-noise measurements of the Mk 20 acoustics research torpedo at 25 kc for vertical angles from 60° down to 60° up are shown in Fig. 26 and compared with the predictions of the surface-reflection theory. In general, the agreement is good, except for the slower speeds and the shallow depths in the down hydrophone positions, where the theoretical predictions are too low. This may be due to the shadowing of the downward-facing hydrophone by the torpedo body at shallow depths. The theory has also been checked approximately for measurements at 60 kc with a Mk 28 torpedo fitted with a tiltable transducer(77).

Variation with Sea State - With increasing sea state, the surface-reflecting region becomes more diffuse, and thus becomes, in effect, shifted forward in angle so as to lie within the more sensitive parts of the beam pattern of an upward-facing hydrophone. At the same time that the zone of reflection (or more properly, scattering) becomes larger, however, it becomes weaker as well.

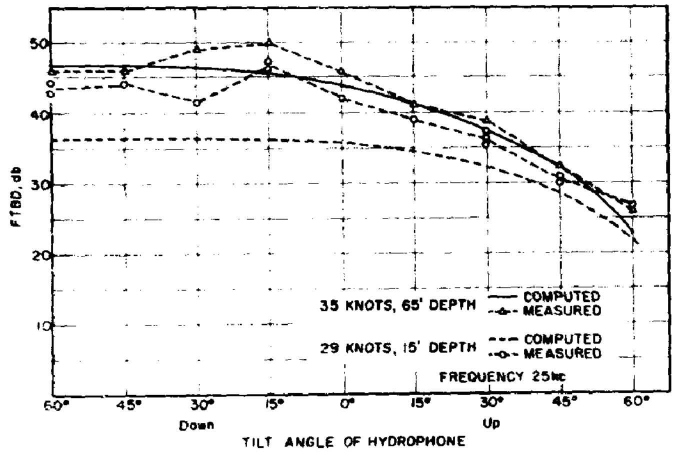


Figure 26 - Variation of FTBD with angle of tilt of an internal hydrophone. Frequency is 25 kc. (Ref. 77)

Measurements with the ORL Mk 20 acoustic research torpedo show only a slight sea-state effect on the self-noise in upward-facing hydrophones. Surprisingly enough, a larger sea-state effect was found for the azimuth and bottom hydrophones, in which the increased surface-scattering for the higher sea states was directly effective(77). In all cases, the measured levels were far higher than would be expected if ambient sea noise were the sole source of noise.

Self-Noise Levels in Existing Torpedoes - A compilation of self-noise levels on various torpedoes measured by the Ordnance Research Laboratory has been given in a recent paper(81), which gives in addition, a good summary of present understanding of torpedo self-noise. Four figures copied from this paper are presented in Fig. 27; three of the plots give self-noise levels as a function of speed; the fourth shows levels vs. running depth at various constant speeds. The levels shown on these plots are axial plane-wave levels rather than isotropic levels, and have 0.0002 dynes/cm^2 as reference instead of 1 dyne/cm^2. Because of the uncertain or unknown directivity indices for all the torpedoes shown, it has not been felt feasible to convert this data to isotropic levels.

Summary - The surface-reflection theory, modified so as to include scattering from a finite area on the surface as well as reflection, is thus seen to provide valid predictions of torpedo self-noise wherever (a) the surface path is the dominant one, and (b) the propellers or the tail section, or both, constitute the primary noise source. These conditions occur for most torpedoes. There are, however, exceptions. For example, in low-speed Mk 20 torpedo runs, machinery noise and hull transmission were believed to predominate, and there was no influence of sea state on the levels of the bottom and azimuth hydrophones. Whenever there are no isolation joints between the hydrophones and the torpedo motor, the direct shell transmission path appears to override the self-noise of bottom and azimuth hydrophones by at least 5 db. This appeared to be the case for measurements of self-noise in a Mk VIII torpedo having no acoustic treatment(82). In such exceptional cases the surface-reflection theory is of no value in prediction. Nevertheless, it would appear that of all the vehicles on which underwater sound transducers are mounted at the present time, the torpedo is the vehicle for which the self-noise is the best understood, and the one for which predictions of self-noise levels in advance of actual field trials can be made with the most assurance.

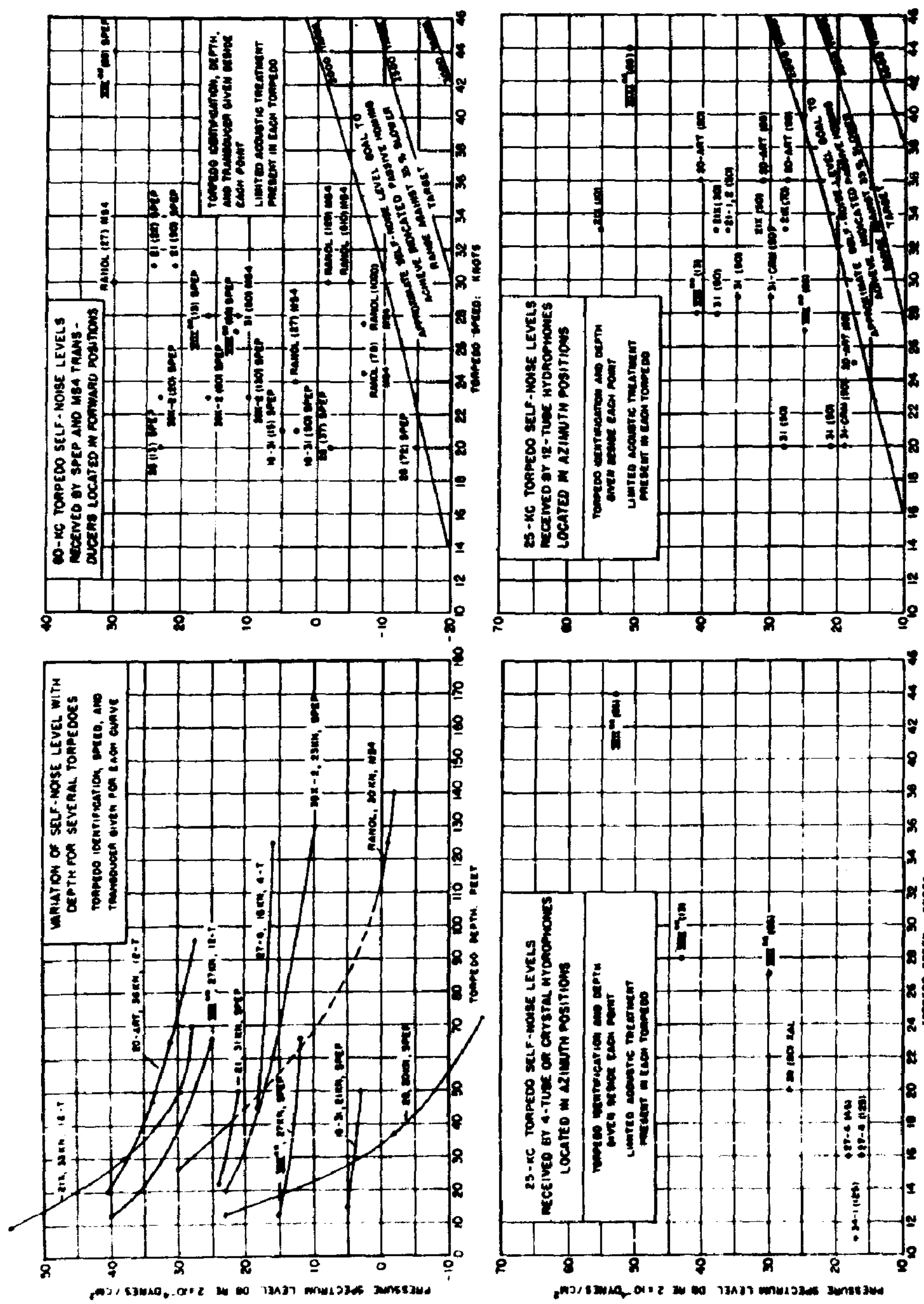


Figure 27 - Self-noise levels in various torpedoes, showing their variation with speed and running depth. The levels given are axial plane wave levels rather than isotropic levels, and are referred to 0.0002 dyne/cm^2, instead of 1 dyne/cm^2. (ORL data copied from Ref. 81)

SELF-NOISE IN SHIP-TOWED SONAR

In ship-towed sonar systems the transducer is placed within a streamlined body and towed at depth by means of a faired cable or a tow chain from the towing vessel. The advantages of towed sonar are said to include the freedom from "quenching" (the attenuation and noise produced by the bubbles swept down around a hull-mounted dome by the motion of the ship), the ability to take advantage of thermal gradients favorable to transmission by selection of transducer depth, and an enhanced stability in rough weather.

The principal acoustic problem involved in the design of towed systems is that of achieving self-noise levels no higher—and if possible, less—than the levels in comparable hull-mounted systems. This aim has not, as a general rule, been achieved, although various engineering solutions have been attempted in order to reach this goal without sacrificing necessary mechanical security. Towed bodies have included specially designed streamlined shapes, modified domes, and lead spheres. The towlines used have included both faired and unfaired cables of various types and the articulated strut developed by WHOI. With the exception of one early trial, in which the towing was done from the bow of the vessel, all of the postwar systems built in this country have been towed from the side of the ship.

During the war, some experiments were made with hydrophones towed from the stern of a vessel(30), and the British obtained extensive self-noise data during trials of a stern-towed hydrophone for the listening detection of torpedoes(84). One interesting effect that was evaluated was the influence of the wake of the towing ship in reducing the self-noise of a hydrophone towed at shallow depth at a distance of 150 yards astern. The attenuation of the wake was found to be high enough, even at frequencies between 200 cps and 6.4 kc in shallow water, to substantially eliminate the noise coming from the towing vessel. More recently, the Canadians have conducted trials of stern-towed transducers in connection with the development of variable-depth sonar(85), but only preliminary background noise measurements appear to have yet been made.

Sources of Self-Noise in Ship-Towed Sonar

In an ordinary hull-mounted transducer, it is apparent, as we have seen, that its self-noise is created in various diverse ways by the vessel to which it is attached. Similarly in a towed transducer, the towing vessel has proved to be the major source of noise under most conditions. In addition, the tow cable and towed body may themselves be a source of noise, especially if they are poorly designed or are mechanically defective.

There have been many experimental results indicating that the self-noise originates at the towing ship and travels via the direct path between the ship and the towed body. In an early towed sonar (for example, that installed on MALOY (EDE 791) in 1950) WHOI found an increase of self-noise of as much as 15 db when the towed directional transducer was pointed along the bearing of the engine room and screws(86). Similar observations(87) were made with the AN/SQS-6(XN-1) system installed on ROBINSON (EDE 220) and BLACKWOOD (DE 219), and with the QHB transducer towed from MALOY(46,88,89). From these latter trials by USL it was concluded that on forward bearings at speeds up to 15 knots the principal source of noise was in the vicinity of the fire and engine room directly above the towed body, while on the after bearings the propellers were the dominant source. Another example is the NRL work with a small-ship system installed on EPCE(R) 851, which suggested that machinery noise coming from the ship is an important source of self-noise(49).

But perhaps the best evidence for the importance of noise originating at the towing vessel lies in the reduction of self-noise that may be achieved by a baffle located above the towed body. The use of a baffling arrangement, consisting of an overhead cover and wings extending beyond the sides of the towed body, gave reductions of from 5 to 10 db, depending on bearing, for towing speeds between 5 and 15 knots with a towed QHB sonar at 25 kc(62,89). In these

tests, the water depth was of the order of 100 feet. Although no adequate baffling was provided against the bottom reflection, other trials with the towed QHB transducer indicated no variation of self-noise level with water depth from 10 to 1000 fathoms(90). Larger reductions than those mentioned above could probably have been obtained if a better shielding material for use in the baffle had been available. Indeed, the search for a suitable baffle material has proved to be a surprisingly difficult matter, although some progress in this direction appears to have been made recently(70).

Although the towing ship is the principal noise source at ordinary echo-ranging frequencies, the towing cable is often the major offender at lower frequencies. For example, NEL found that the cable vibration arising at the air-water interface provided the major noise problem at low frequencies at speeds up to 15 knots(91), while WHOI trials showed that the prominent noise in the towline towing an ATERE body was in the neighborhood of 100 cps(92).

It is of interest to note that some peculiar noise sources were observed in early towed sonar trials. Two examples that may be mentioned are the hammering of a loose piece of metal left in towed body, and the strong low-frequency tone attributed to the vibration of the tail fins, observed by WHOI during the MALOY trials(86).

Self-Noise Levels in Ship-Towed Sonar

In discussing the self-noise levels in towed systems, we shall consider only the differences in level between the self-noise of the towed transducer and that of an identical hull-mounted unit. This comparison is just what is of interest to the design engineer, and much of the data are available in this form in the literature. The reader concerned with actual levels in towed systems may use the comparative information to follow in conjunction with the data for surface ships given earlier in this report.

Effect of Speed - The most extensive series of measurements of self-noise levels in towed transducers has been made on MALOY (EDE 791), first by WHOI with an XQB searchlight transducer(86) and later by USL using a QHB scanning transducer(88). Both utilized the overside rig and articulated towing strut developed by WHOI. Some of the results of these trials that may be mentioned are the following. At a frequency of 17 kc with 240 feet of towchain out, the self-noise level was found by WHOI to increase by 8 db when the speed rose from 5 to 15 knots, and was 0-5 db higher than that of a hull-mounted transducer at all depths between 50 and 240 feet; this difference was independent of speed between 5 and 17 knots(86). Other observations by WHOI at frequencies between 17 and 26 kc indicated differences of -2 to +10 db for the towed self-noise levels relative to the hull-mounted levels(86). With the USL system on MALOY the levels increased at an erratic rate of between zero and 2 db per knot at speeds below 10 knots, and at a rate of 1 db per knot between 10 and 15 knots(90). More specifically, the self-noise level of the towed QHB transducer at a depth of 70 feet at a speed of 15 knots was found to be 8 db higher than the hull-mounted QHB(90).

Various other observations of higher levels in self-noise towed sonar systems appear in the literature. With the AN/SQS-6(XN-1) gear installed in ROBINSON, for example, OPDEVFOR found the towed self-noise levels to be higher than the shipboard levels by an amount which decreased with both increased speed and increased towing depth(87). During more recent trials on PCE-R 851, NRL found the self-noise levels of the towed transducer at a depth of 20 and 40 feet to be not only higher than the hull-mounted levels by 5 db at zero speed, but to increase more rapidly with speed(49); these excessive levels at the higher speeds were attributed to the fact that the towed body tended to tow more nearly under the screws at high speeds.

On the other hand, there have been reported instances of levels in towed sonar no higher than the levels of conventional systems. For example, during the first full-scale trials of a towed sonar, when the "fish" was towed at a depth of 40 feet from an A-frame mounted on the

bow of EPC-849, no marked differences were found between the towed levels and those of a hull-mounted transducer(92). Similarly, a downward-looking UQN echo-sounding transducer installed by WHOI in a small fish and towed from the R/V ALBATROSS was generally more quiet than conventional hull-mounted echo-sounding systems, even though a similar towed unit on R/V CARYN was excessively noisy at normal towing speeds(93).

These discordant results are indicative of an extremely complex subject. Because of the many acoustic and mechanical variables which affect the self-noise of towed systems, and in the absence of systematic investigations of the behavior of these variables, much additional study of a research nature—rather than measurements on operational towed systems—will be required before the subject can be said to be adequately understood.

Effect of Towing Depth - Since the principal sources of self-noise in towed systems at echo-ranging frequencies are probably located on and near the towing ship, one would expect that self-noise levels would fall off as the towing depth is increased. That this actually occurs was shown by measurements of the towed QHB transducer towed from MALOY (EDE 791) which indicated a decrease of 6 db per doubling of the towing depth between 30 and 90 feet(90), in confirmation of the simple assumption of spherical spreading from a point source.

A similar behavior with depth was observed for the AN/SQS-6(XN-1) variable-depth sonar aboard BLACKWOOD (DE 219) for depths between 20 and 120 feet, particularly at low speeds(87).

Even on this single aspect of a complex subject, however, discordant observations have been reported. Measurements by NRL on a small-ship system indicated higher self-noise levels at the deeper towing depths, with an increase of 8 db as the fish was lowered from 20 to 40 feet while being towed at 10.5 knots(54). In later trials on PCE-R 851, a rise in level of 15 db was observed for the same change of depth; the levels increased with increasing speed(49). As mentioned above, these peculiar effects were attributed to the tendency of the fish to tow further aft, beneath the screws, as the towing speed was increased.

Spectrum of Self-Noise in Ship-Towed Sonar - Our knowledge of the spectrum of towed-sonar self-noise is restricted to the kilocycle-frequency range of interest in echo-ranging; existing measurements lie between 5 to 30 kc. Even within this range, available data, largely from three trials, are somewhat contradictory. NRL, using identical transducers in a fish towed by a faired cable and in a dome attached to the towing ship, made comparative self-noise measurements at 5-kc intervals between 5 and 30 kc. No important differences in spectra at any depth or speed were found(54). On the other hand, in the early tests of the variable-depth sonar on MALOY (EDE 791) using an articulated strut as the towline, WHOI found the noise levels to be especially high, compared with those for the hull-mounted transducer, at frequencies below 10 kc(86). The spectrum of the VDS noise was much steeper in the octave 5 to 10 kc. A steeper spectrum slope was also found by WHOI(92) for the earlier fish towed from the bow of EPC-849. In this case it was suggested that the bow wave was a principal noise source, especially at high speeds, when the noise level rose and fell concomitantly with the pitching of the ship.

The origin of these differences warrants much greater study to aid in the understanding of the sources of self-noise with a view to self-noise reduction. This is particularly necessary in view of the increasing emphasis on lower frequencies for echo-ranging applications. As we have seen in discussing the sources of self-noise, the prominent noise sources at the lower frequencies are probably no longer on the towing ship, but may be the towing cable, the rig, or vibration in the towed body itself. Consequently, these may require further study for lower-frequency applications.

Fluctuation of Self-Noise - As has been pointed out earlier, one of the advantages of towed sonar as compared with hull-mounted sonar is that the transducer operates in the clear water away from air bubbles entrapped by the hull or occurring naturally near the surface, so that

quenching is eliminated. In consequence, towed sonar has a much steadier noise output, and is free from the familiar noise bursts observed in hull-mounted transducers. All studies of self-noise in towed sonar have confirmed this difference in character in the noise between hull-mounted and towed transducers(54,86,92). In general, rough seas have little effect on towed sonar self-noise levels, and various studies have shown that there is no change in level up to sea state 3(86,90). In fact, it has been suggested that self-noise levels may be lower in rough seas as a result of the masking effect of bubbles trapped beneath the ship.

It is interesting to note, however, that although the self-noise level is steadier in towed than in hull-mounted sonar systems, it may show greater day-to-day variations. USL has found, for example, when towing a QHB transducer from the MALOY (EDE 791) at 15 knots at a depth of 50 feet, that while the day-to-day variations were 12 db in the fish, they were but 4 db in a similar hull-mounted transducer(46). At this speed, there was probably a difference in origin of the predominant noise sources of the two transducers, with hydrodynamic noise dominant on the hull-mounted unit and machinery noise on the towed transducer; the greater variation observed in the fish may have been due to different machinery operating conditions from day to day(46).

SELF-NOISE IN AIRBORNE SONAR

Although attempts were made during the war to tow hydrophones from a blimp(30), airborne sonar is essentially a postwar development. Two systems have been evolved. The first, dipped or dunked sonar, is particularly suited to the peculiar characteristics of the helicopter and is also used from blimps. The second, air-towed sonar, requires the use of a blimp as the towing vehicle. In what follows, the self-noise in each of these types of airborne sonar will be discussed separately. It will be apparent that, as in other types of sonar, the vehicle plays an important part in determining the self-noise level. It should be noted that the levels reported refer to specific combinations of aircraft and sonar. In the future, aircraft and other developments may permit the use of other aircraft-sonar combinations. Prediction of self-noise levels in such systems will require (as in the case of other systems discussed earlier in this volume) a thorough understanding of the sources of self-noise.

Dunked Sonar

In dunked sonar systems, which are used from hovering aircraft, the transducer is suspended at some distance beneath the sea surface and kept as stationary as possible. Directional transducers are used for echo-ranging at conventional frequencies; provision is made for listening at lower frequencies.

In the absence of any noise from the aircraft, it would be expected that equivalent isotropic background levels observed in these transducers would approach ambient-noise levels. Somewhat higher levels might be expected since the transducer is never completely stationary; its motion and that of the supporting cable through the water would be expected to generate some hydrodynamic noise. In general, however, we should expect such hydrodynamic noise to be of little consequence, particularly at echo-ranging frequencies where its spectrum level certainly falls off more rapidly with frequency than that of ambient noise. Experience with blimp-dipped sonar, where the transducer is supported from a float at the surface, confirms that the noise levels are low and approach ambient, although it is suspected that below about 400 cps noise from the blimp may be important(103).

Self-noise measurements in helicopter-borne systems have shown high levels(94,95). Early tests at Patuxent of AN/AQS-1 in an ARP-1 helicopter gave self-noise levels 16 db above ambient noise for sea state 2 at frequencies between 28 and 34 kc; in the audio band centering at 5.5 kc levels were 22 db above ambient for that sea state(94). These high noise levels are unquestionably due to the helicopter, and almost certainly to rotor noise, for measurements in

hydrophones placed at the normal depth of the transducer show corresponding increases of noise level when the helicopter hovers over them. In tests at Key West, for example, the spectrum level of the noise at 34 kc measured in a hydrophone under these conditions was -50 db rel. 1 dyne/cm^2, compared with -47 db in the earlier Patuxent tests; while at 5 kc the noise levels were 20 to 25 db above ambient(94). More recent NRL tests have given essentially similar results. It was found that the noise levels measured with a substantially nondirectional hydrophone suspended at a depth of 40 feet below an HRP-1 helicopter hovering at 10-20 feet were 20-25 db higher than measured water noise in the frequency range 1-30 kc(96).

This data clearly indicates the importance of aircraft type, since the helicopter is undoubtedly the noise source in helicopter-dunked sonar.

Air-Towed Sonar

The limitations of performance of other types of aircraft have restricted the use of air-towed sonar to blimps. Such systems are essentially similar to ship-towed systems, since the transducer is mounted in a streamlined body towed at depth. Early work on these systems was concerned with the mechanical and hydrodynamic problems(97). It was necessary to design a system which would permit lowering and recovery of the body through the water surface at speed. In addition the body itself must be capable of being towed at speed, should maintain its depth, and should not cavitate(98). Two types of body were developed. The first, called ATERE, had a submerged weight of 900 pounds in order to maintain its depth. The second, called WHATS, weighed 275 pounds submerged and used depressor fins for maintaining its depth. Although the ATERE was considered to be probably the optimum towed body, its dead weight of 1300 pounds in air was unduly high(97).

In early tests with the ATERE body, the noise level was excessively high. The towcable, cable trunnion, microphonics, and electrical pickup in the towcable were all found to be important sources of noise(94,97). Considerable improvement was achieved by the use of a faired cable, and this and other improvements reduced the noise levels to ambient levels in the frequency range 15-35 kc for towing speeds up to 15 knots, at depths of 50-75 feet. The self-noise increased at about 1 db/knot for speeds of 15 to 30 knots and at about 2 db/knot above 30 knots(94,99). At a speed of 30 knots the noise level at 28 kc was -52 db relative to 1 dyne/cm^2(94,99). The rise in noise level above 30 knots was believed to be due to cavitation around the tow point or cable fairing(94).

More recent data have confirmed these low noise levels for blimp-towed sonar. For example, when a WHATS body was towed by means of a faired cable, the background level was found to remain near ambient level for towing speeds up to 19 knots, rising at 1.4 db/knot at higher speeds up to 40 knots(100). Here the self-noise was attributed to the mechanical rattle of the cable fairing or the towbar assembly. In other trials it has been found that the blimp-towed AN/AQS-2 sonar can be towed at speeds up to 25 knots before background levels rise above ambient levels(101). As the towing speed increased above 25 knots, the additional self-noise was believed due to a flutter in the towcable(101).

It should be emphasized that these low self-noise levels have been obtained with a blimp as the towing vehicle. In the future, aircraft other than blimps may be used, which will not be so ideal from the self-noise standpoint; then higher levels may then be expected, especially at low towing speeds.

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DEPARTMENT OF THE NAVY
OFFICE OF NAVAL RESEARCH
800 NORTH QUINCY STREET
ARLINGTON, VA 22217-5660

IN REPLY REFER TO
5510/1
Ser 93/057
20 Jan 98

From: Chief of Naval Research
To: Commanding Officer, Naval Research Laboratory (1221.1)

Subj: DECLASSIFICATION OF DOCUMENTS

Ref: (a) NRL ltr 5510 Ser 1221.1/S0048 of 25 Feb 97
(b) NRL memo Ser 7103/713 of 29 Jan 97
(c) ONR Report "A Summary of Underwater Radiated Noise Data, March 1966"

Encl: (1) ONR Report "A Summary of Underwater Acoustic Data, Part I" AD-030 750
(2) ONR Report "A Summary of Underwater Acoustic Data, Part II" AD-039 542
(3) ONR Report "A Summary of Underwater Acoustic Data, Part III" AD-039 543
(4) ONR Report "A Summary of Underwater Acoustic Data, Part IV" AD-039 544
(5) ONR Report "A Summary of Underwater Acoustic Data, Part V" AD-105 841
(6) ONR Report "A Summary of Underwater Acoustic Data, Part VII" AD-115 204
(7) ONR Report "A Summary of Underwater Acoustic Data, Part VIII" AD-105 842

1. In response to reference (a), the following information is provided:

Enclosure (1) was downgraded to UNCLASSIFIED by CNR, 7/29/74;
Enclosure (2) was downgraded to UNCLASSIFIED by NRL, 12/3/90;
Enclosure (3) was downgraded to UNCLASSIFIED by CNR, 7/29/74;
Enclosure (4) was downgraded to UNCLASSIFIED by CNR, 7/29/74;
Enclosure (5) was downgraded to UNCLASSIFIED by NRL, 12/3/90;
Enclosure (6) was downgraded to UNCLASSIFIED by CNR, 7/29/74; and
Enclosure (7) was downgraded to UNCLASSIFIED by CNR, 7/29/74.

Enclosures (1) through (7) have been appropriately stamped with declassification information and, based on the recommendation contained in reference (b), Distribution Statement A has been assigned.

2. To my knowledge, reference (c) AD-396 737 has not been previously reviewed for declassification. Based on our ~~discussions~~ in April 1997, I am still ~~holding~~ it for Dr. ~~Hurdle's~~ comments.

3. Questions may be directed to the undersigned on (703) 696-4619.

Completed
18 Apr 2000
B.W.

Peggy Lambert
PEGGY LAMBERT
By direction